Scaling Laws in Disks and Exoplanets

Testing Planet Formation Theories

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Orion Nebula: HST/ACS (Robberto et al. 2012)


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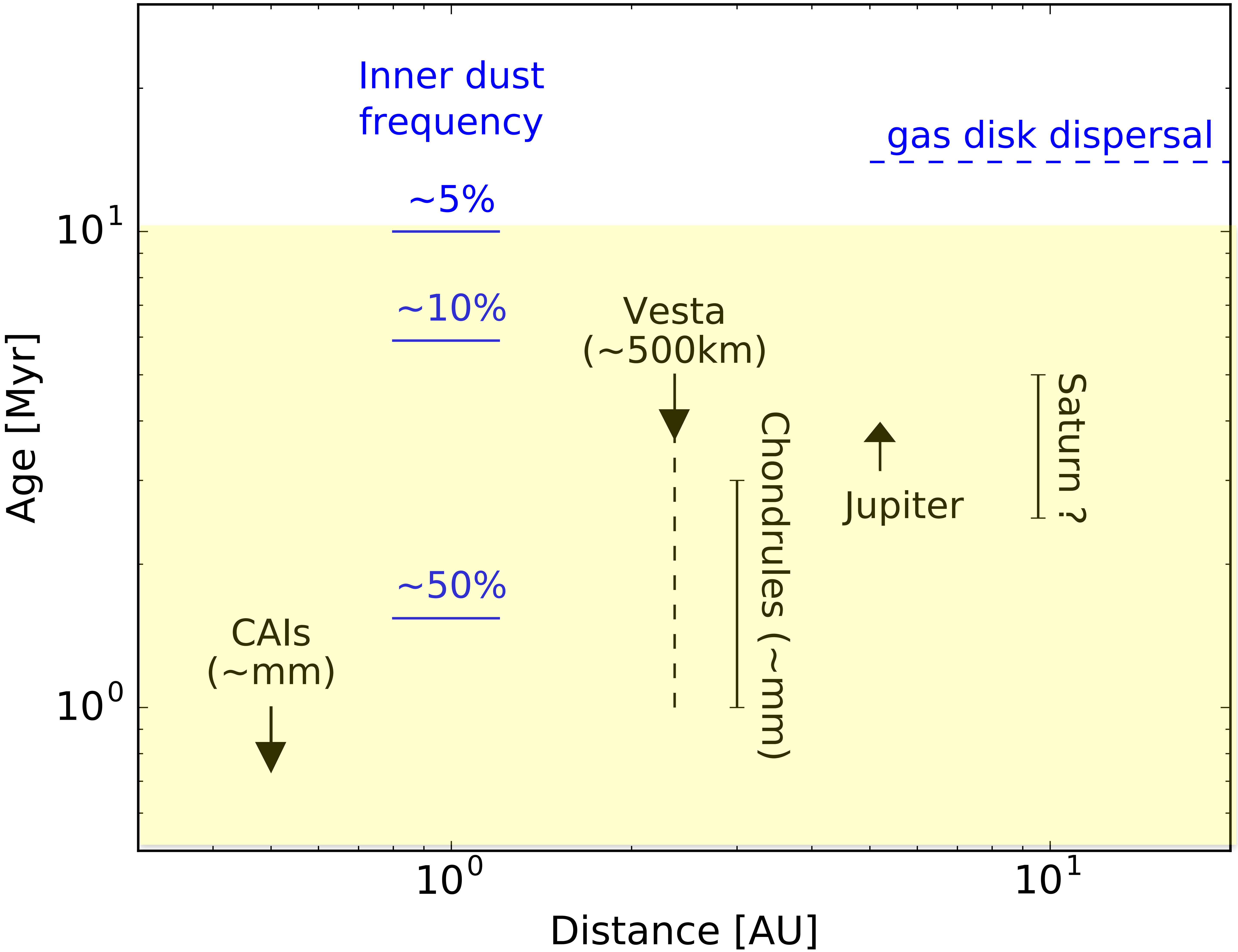
All young (~1Myr) stars have a circumstellar disk
(after accounting for stellar multiplicity, Kraus et al. 2012)

What is the time window for planet formation?

Adapted from Pascucci & Tachibana (2010)



Circumstellar disks:

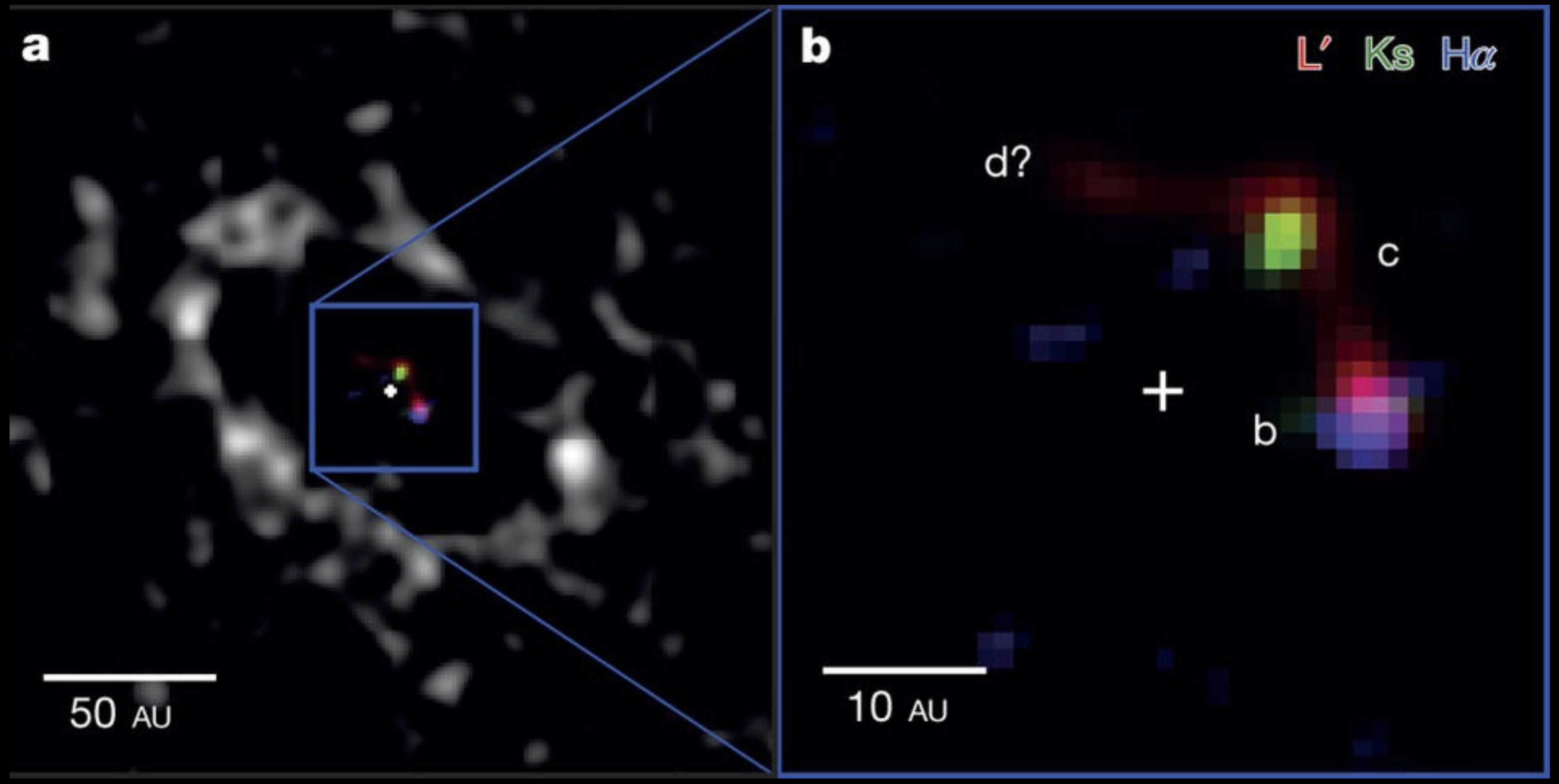
- By ~10Myr only 5% of the stars retain warm dust within 1AU
- Most of the gas is dispersed by ~10Myr

Solar System:

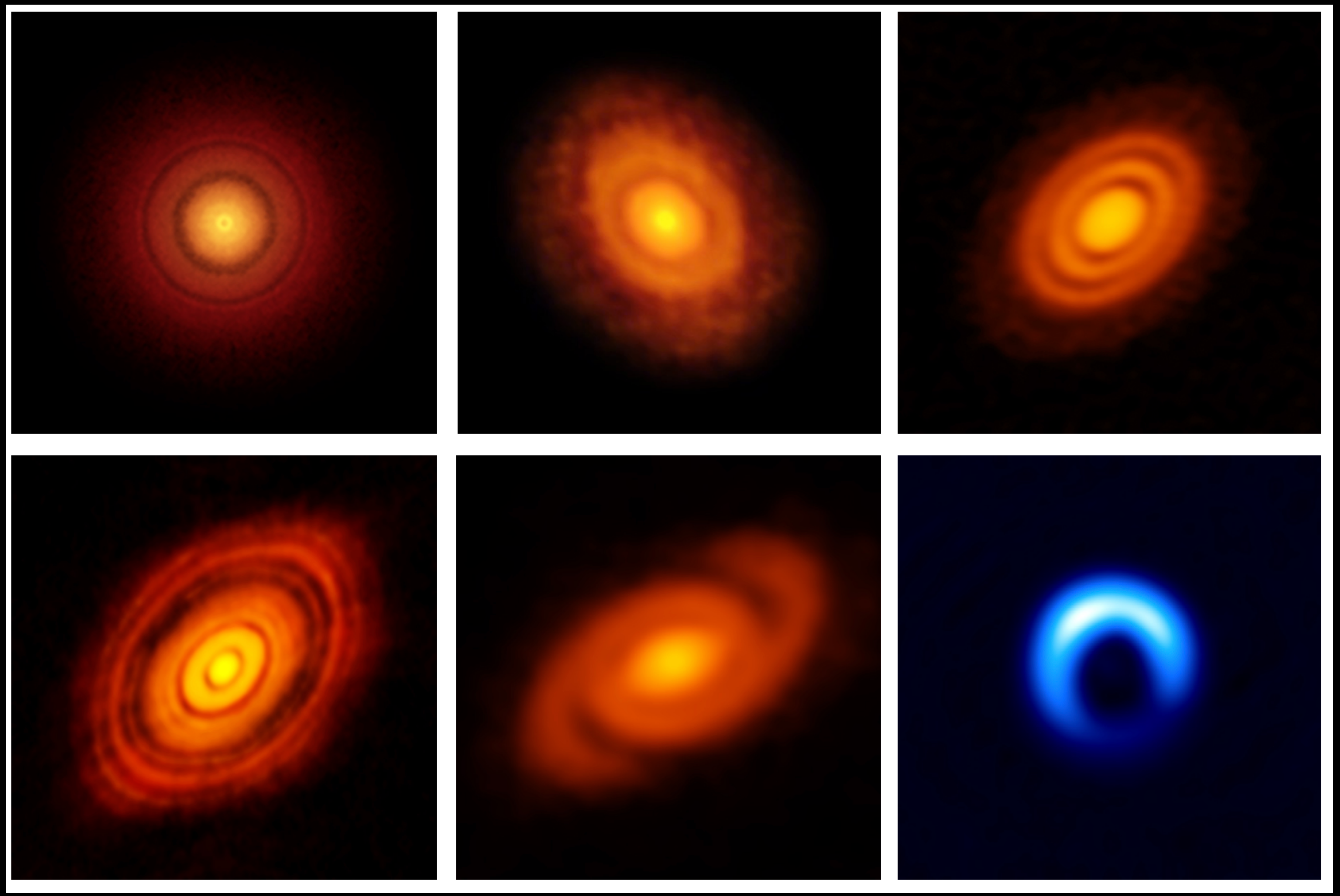
- Asteroids formed within 5Myr from CAIs
- Most likely Saturn formed within 5Myr

Planet-forming disks

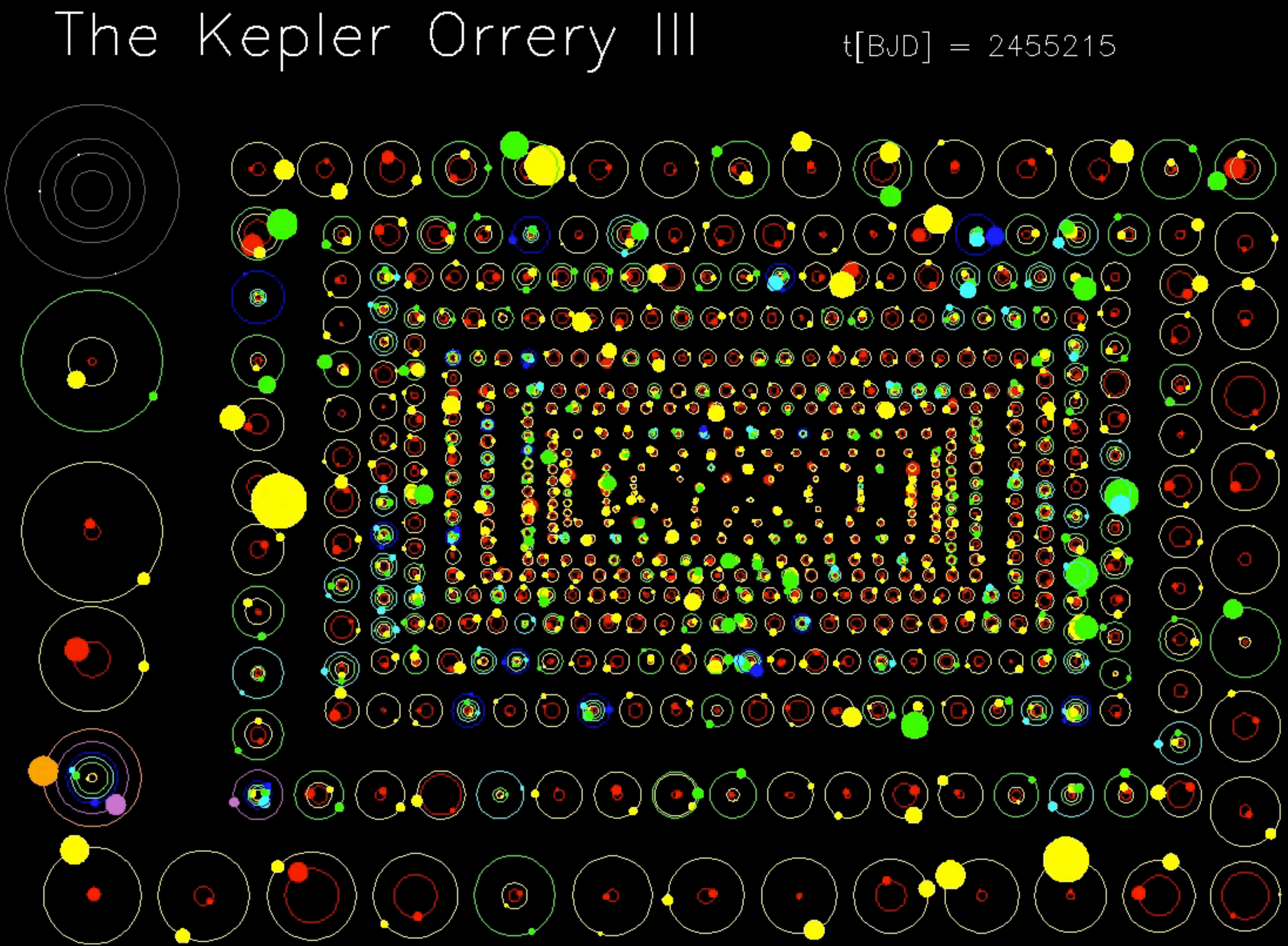
LkCa15 disk and planet candidates, Sallum et al. (2015)



ALMA high-resolution observations of disks



https://almascience.eso.org/alma-science/planet-forming-disks



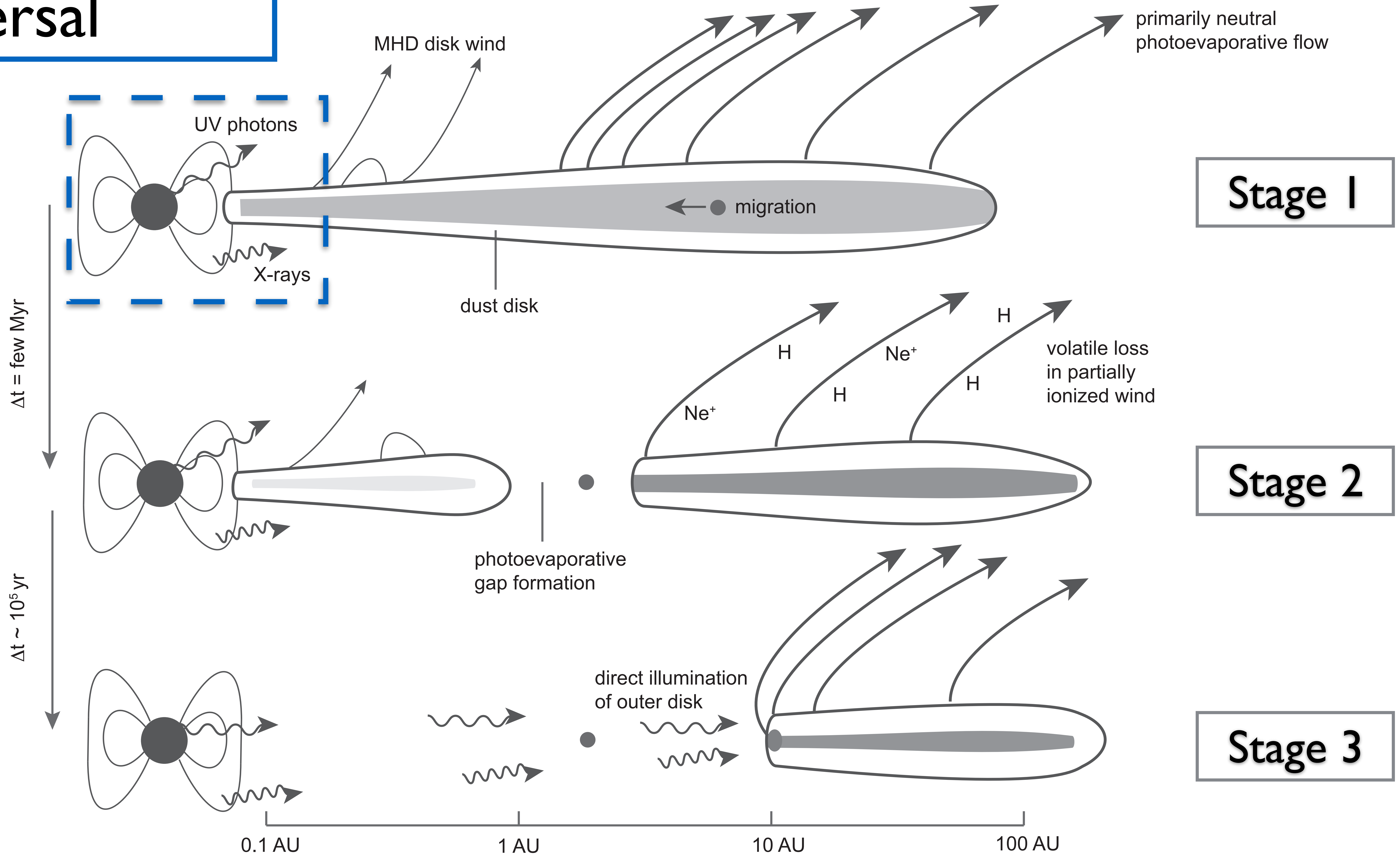
Credit: D. Fabricky

Which disk properties remain imprinted in the exoplanet population?

Which physical processes shape planetary systems?

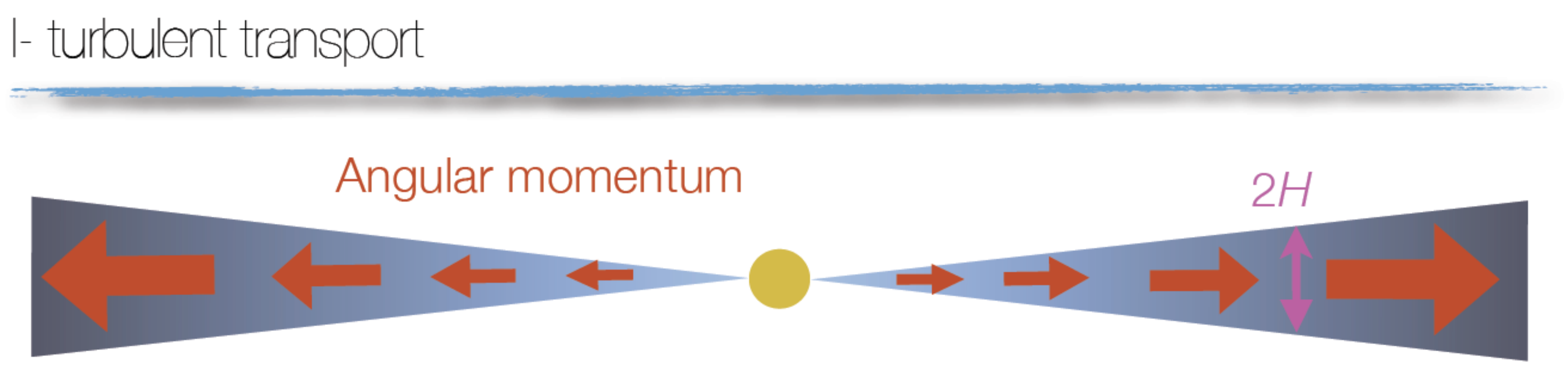
Are there scaling laws in disks and exoplanets?

Stages of disk evolution and dispersal

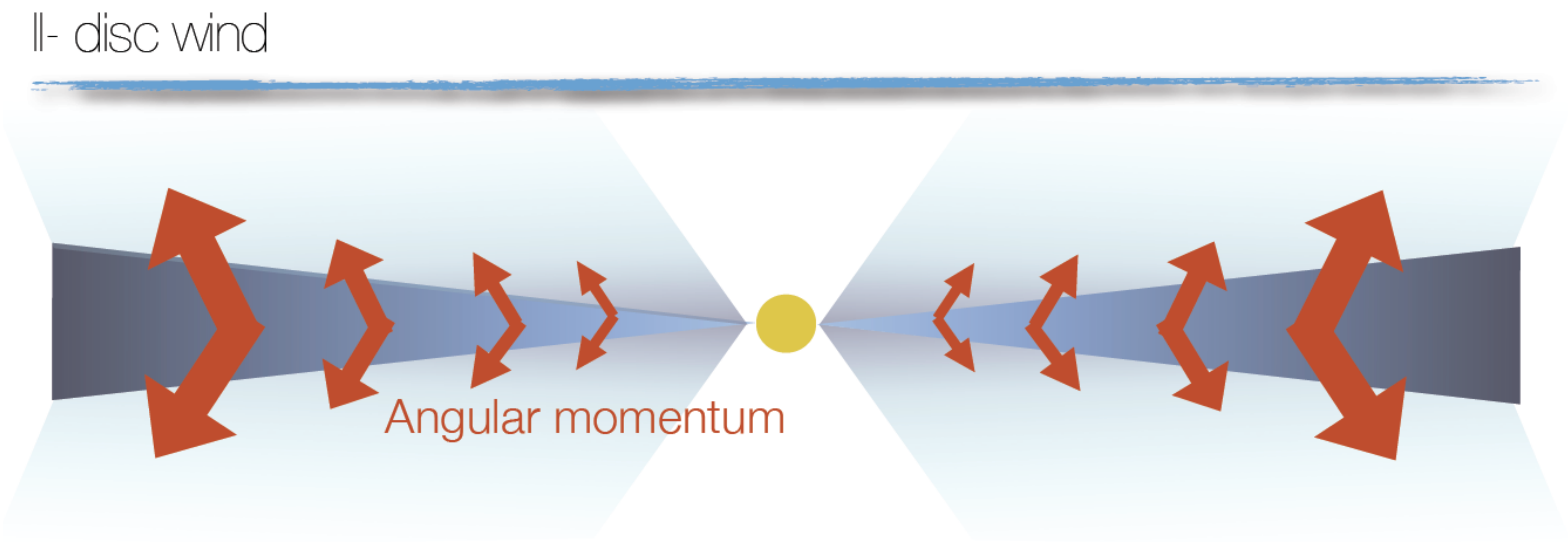


From Alexander, Pascucci et al. 2014 (PPVI review)

How is the accreting gas losing angular momentum?



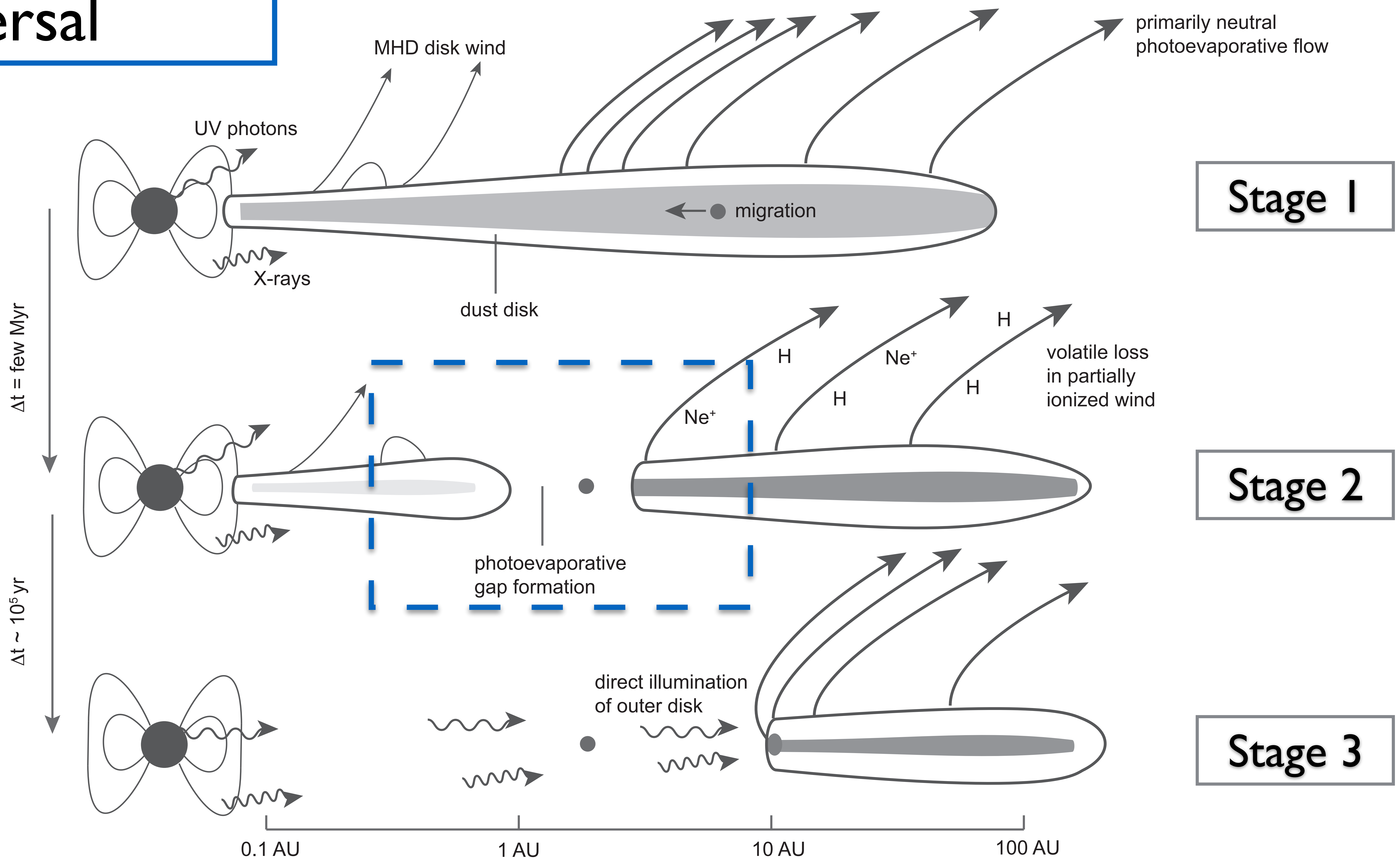
1. angular momentum is re-distributed in the disk



2. angular momentum is extracted from the disk via a wind

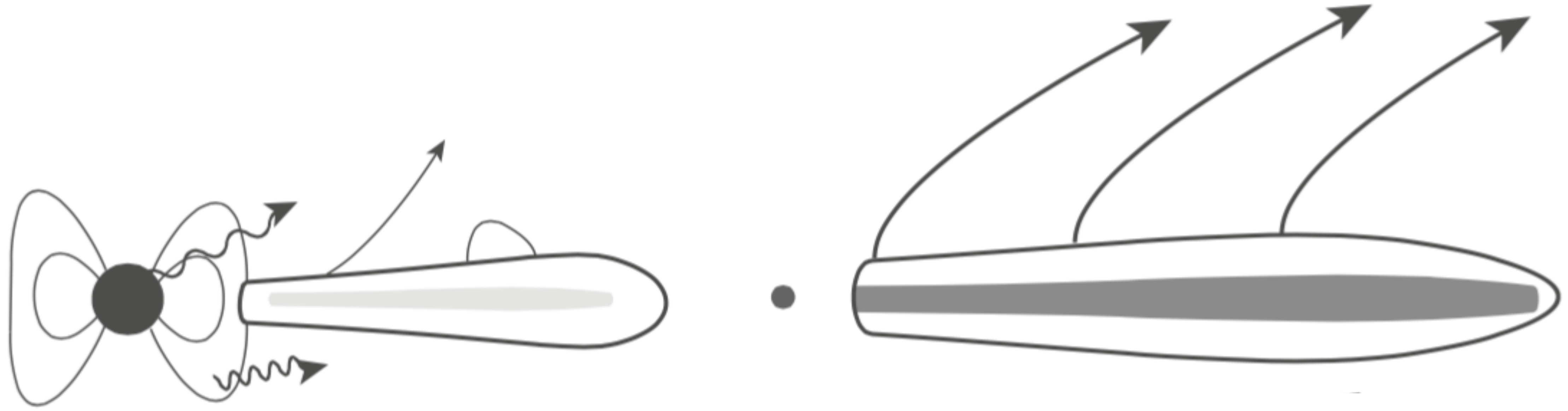
Turner et al. 2014 (PPVI review)

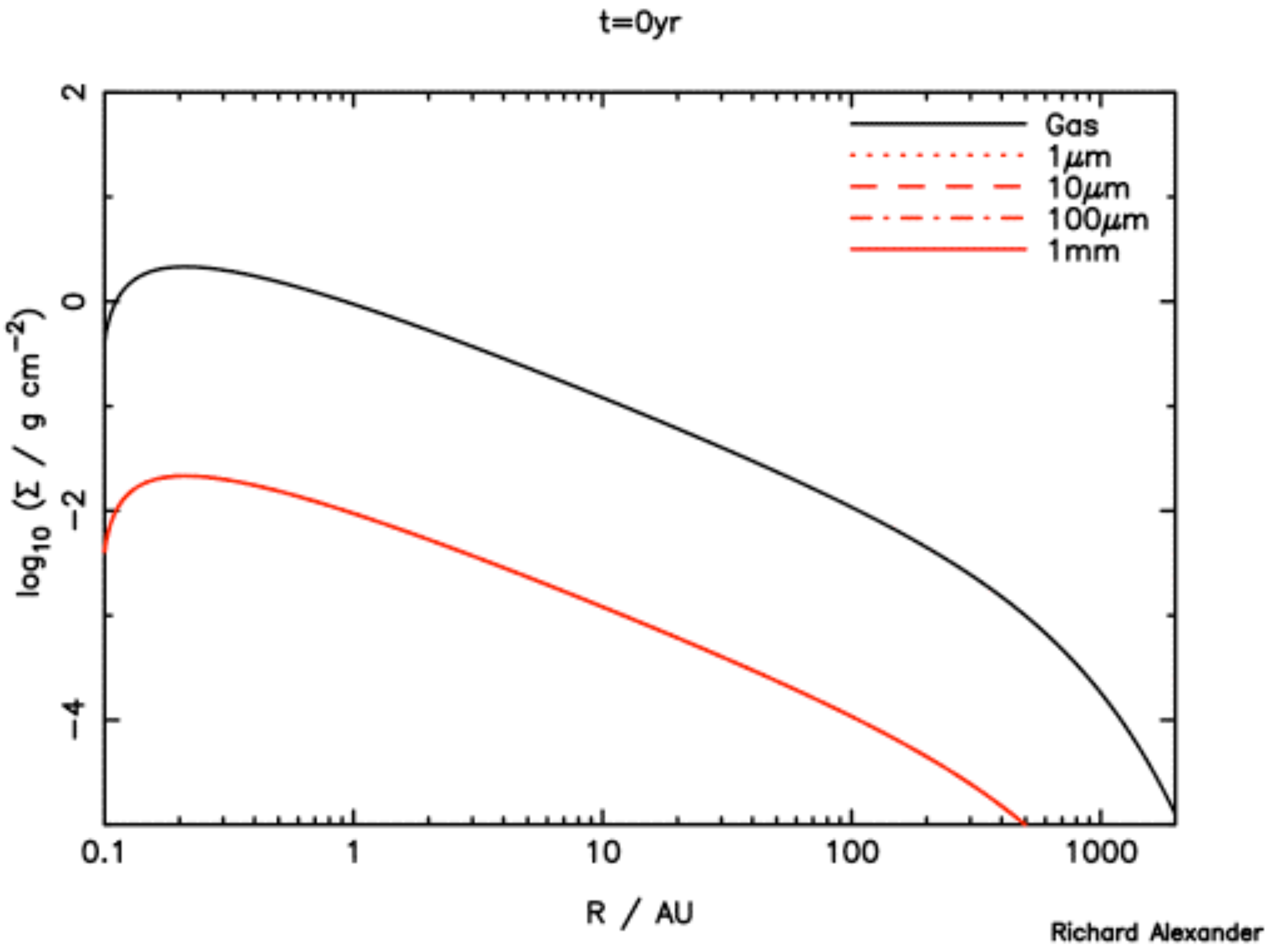
Stages of disk evolution and dispersal



From Alexander, Pascucci et al. 2014 (PPVI review)

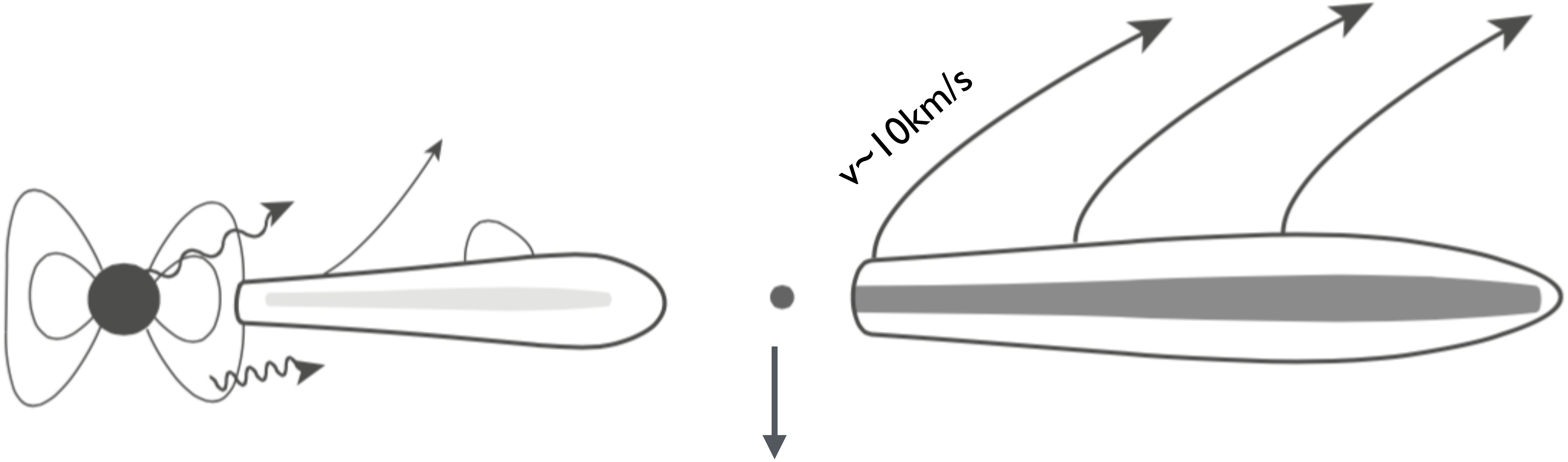
Stage 2: photoevaporation takes over accretion





Stage 2: photoevaporation takes over accretion

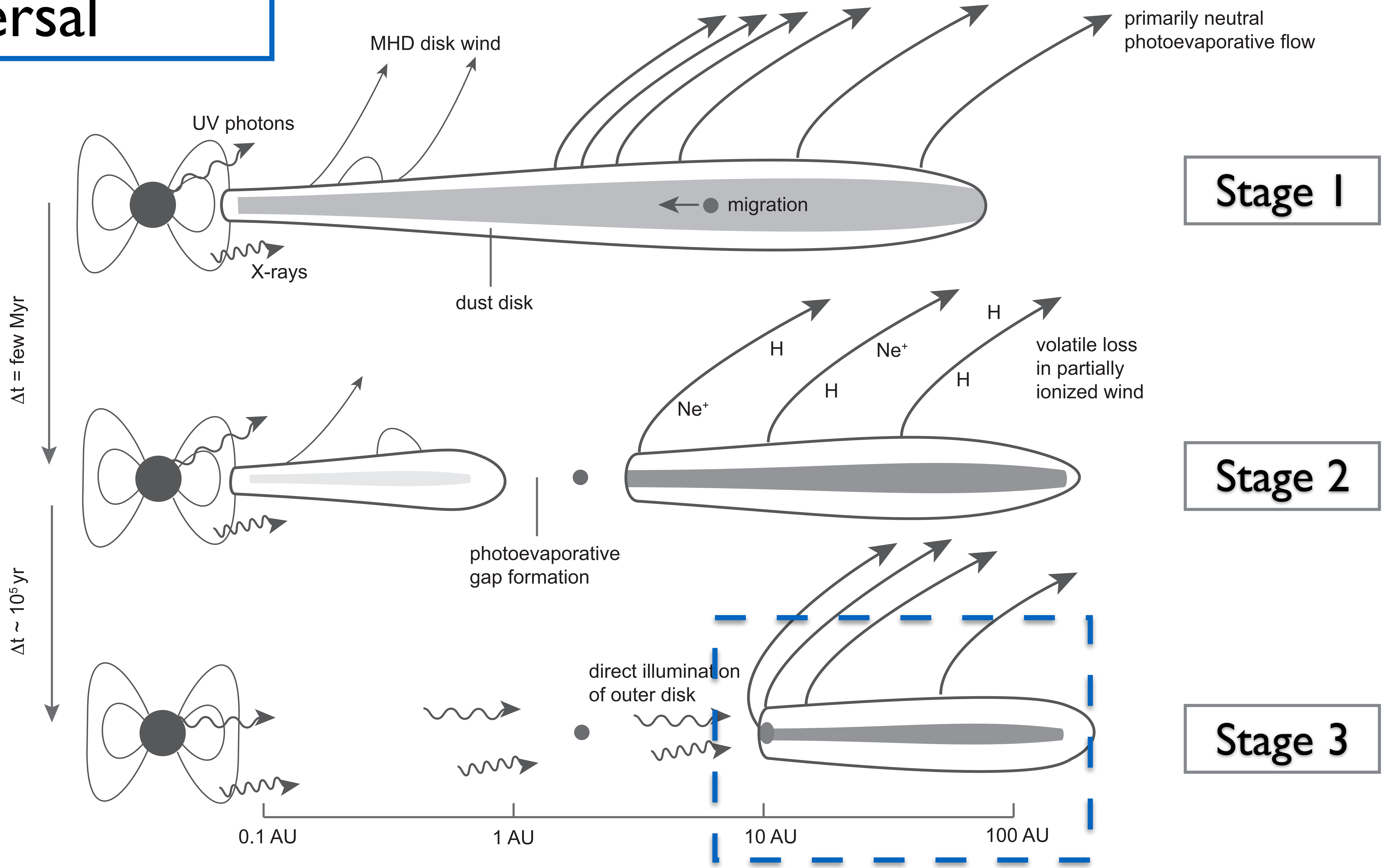
For a solar mass star R_{crit} is at ~ 1AU



$R_{crit} \sim M_{star}/c_s^2$

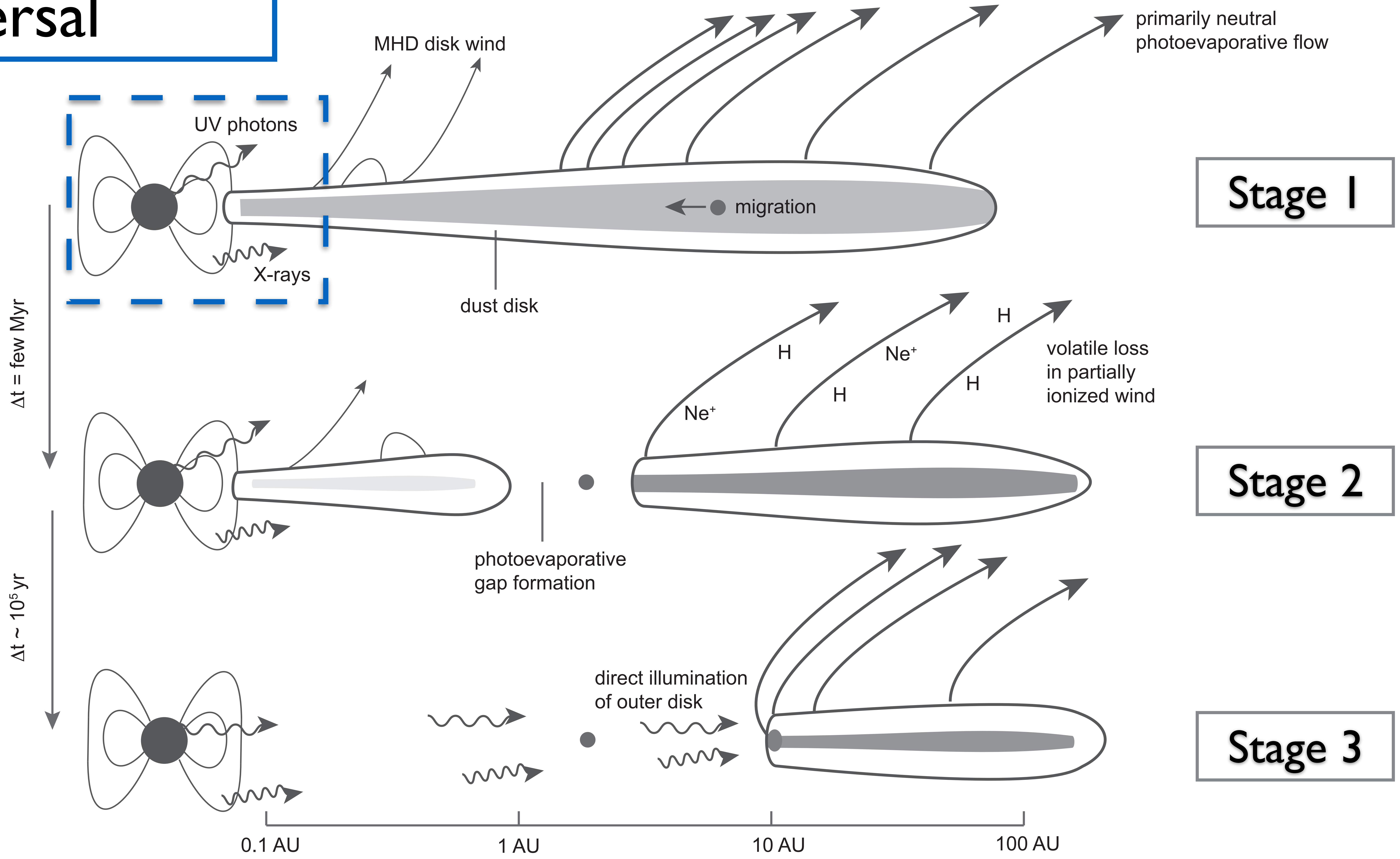
Photoevaporation is driven by high-energy photons from the central star (EUV, X-rays, FUV). Reviews by Alexander, Pascucci et al. (2014); Gorti et al. (2016); Ercolano & Pascucci (2017)

Stages of disk evolution and dispersal



From Alexander, Pascucci et al. 2014 (PPVI review)

Stages of disk evolution and dispersal



From Alexander, Pascucci et al. 2014 (PPVI review)

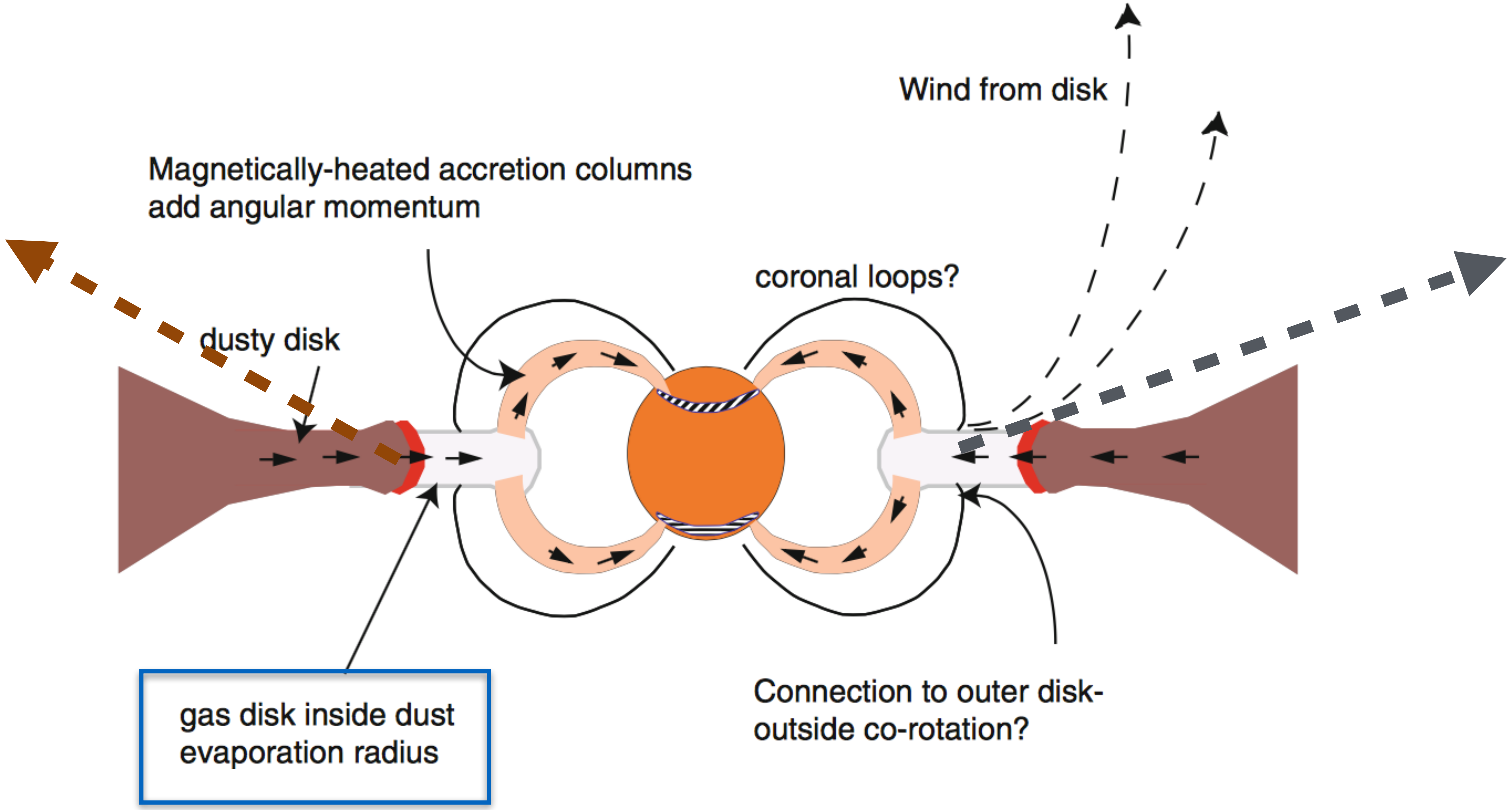
The inner edges of planet-forming disks

$R_{dust} \sim (L_{star})^{1/2}$

$R_{dust} \sim (M_{star})^{0.7}$

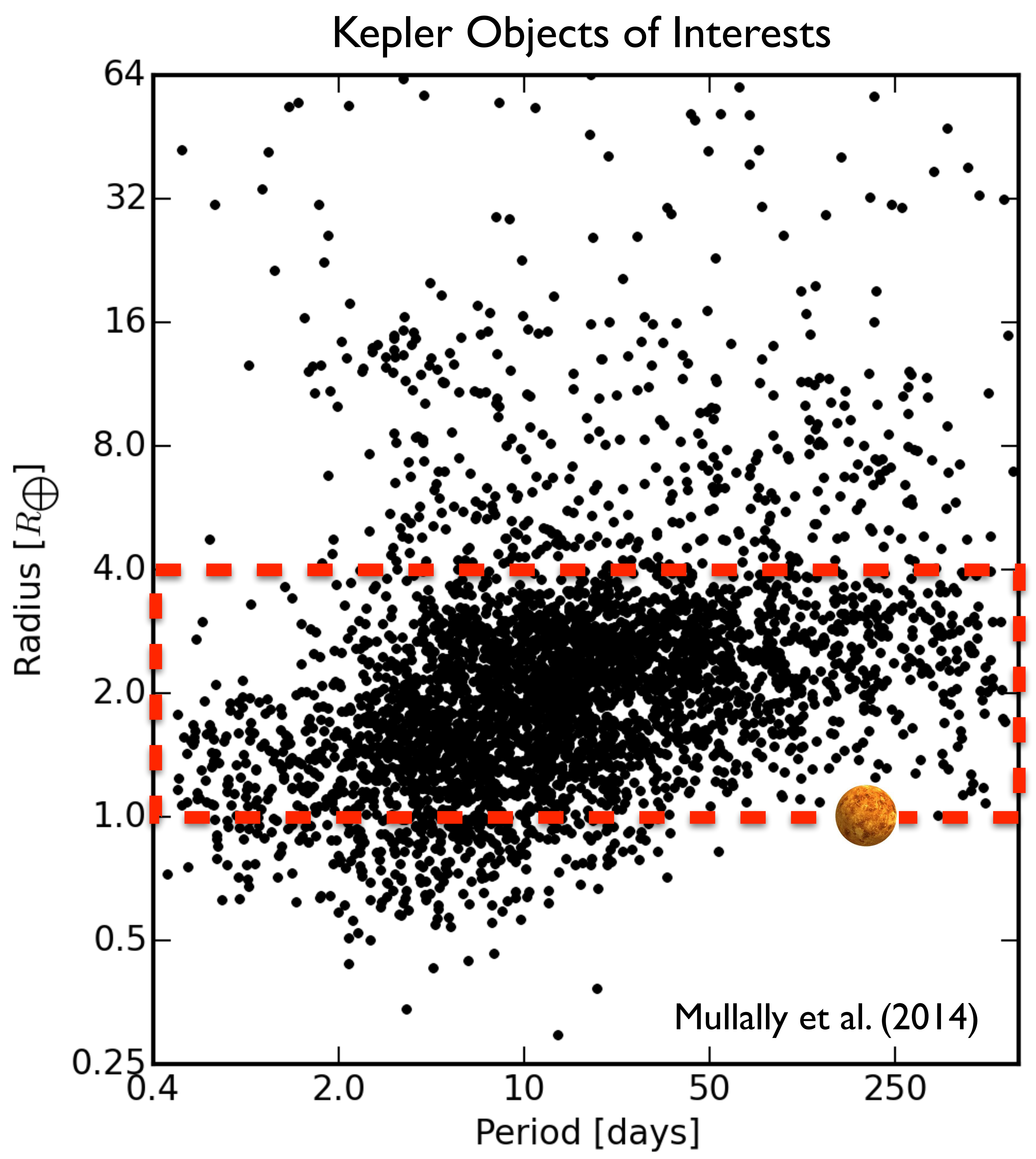
$\Omega_{disk} = \Omega_{star}$

$R_{gas} \sim (M_{star})^{1/3}$

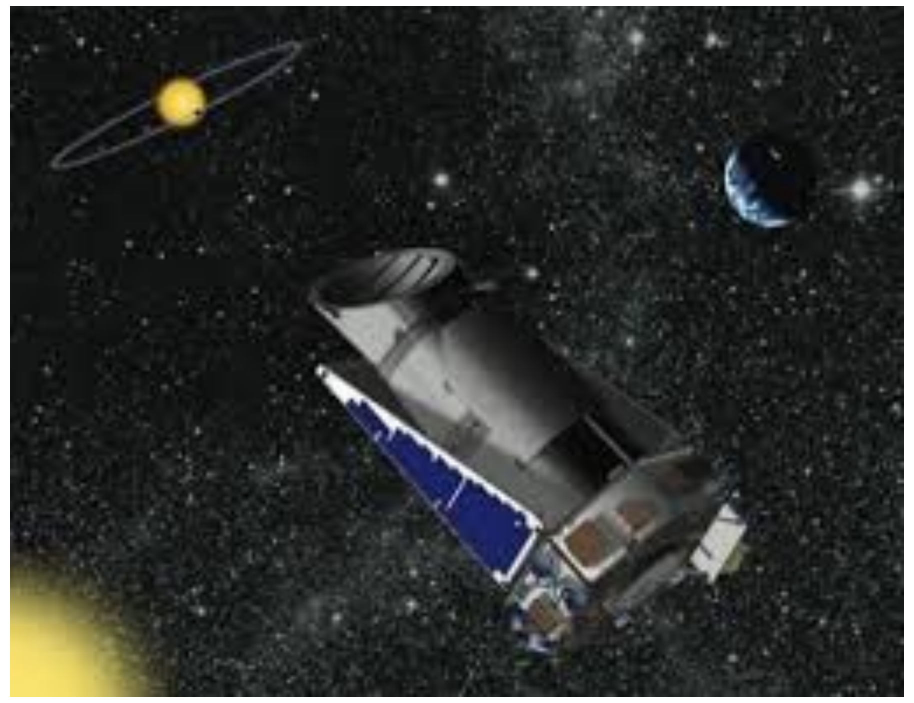


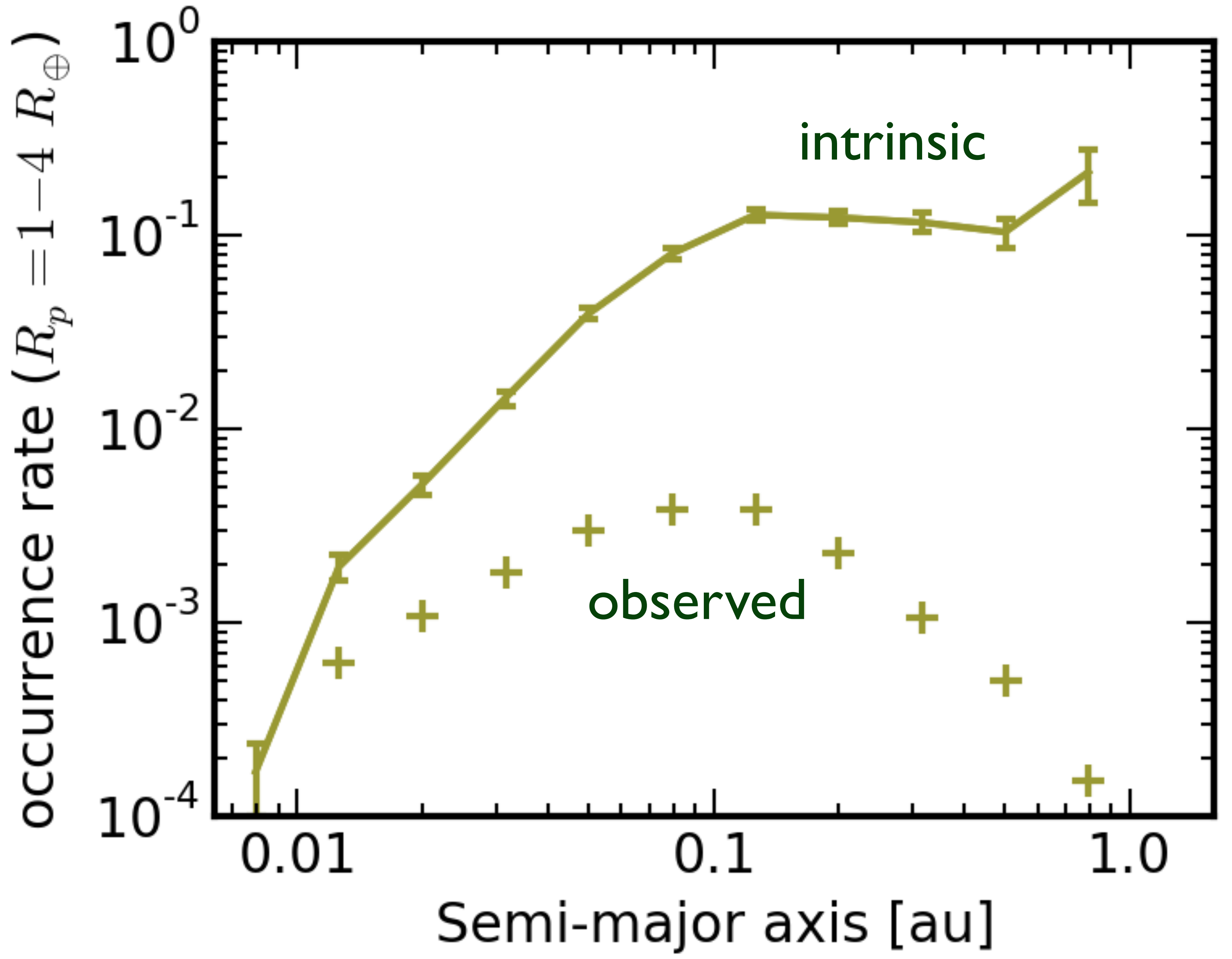
Disk inner regions: Dullemond & Monnier (2010)

Accretion onto young stars: Hartmann, Herczeg, Calvet (2016)



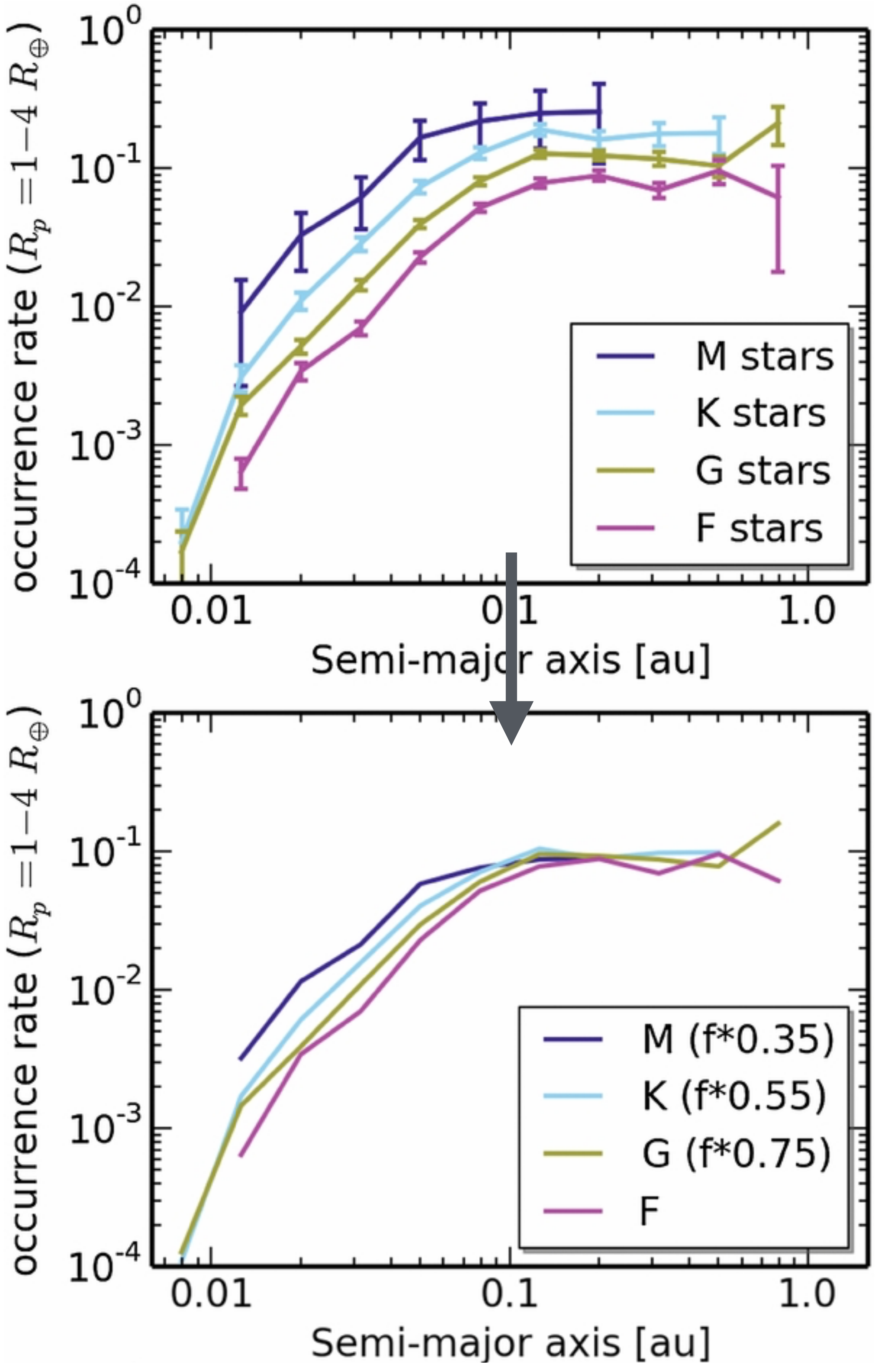
Kepler Objects of Interests
64
32
16
8.0
4.0
2.0
1.0
0.5
0.25
0.4
2.0
10
50
250
Radius [$R_\oplus$]
Period [days]
Mullally et al. (2014)





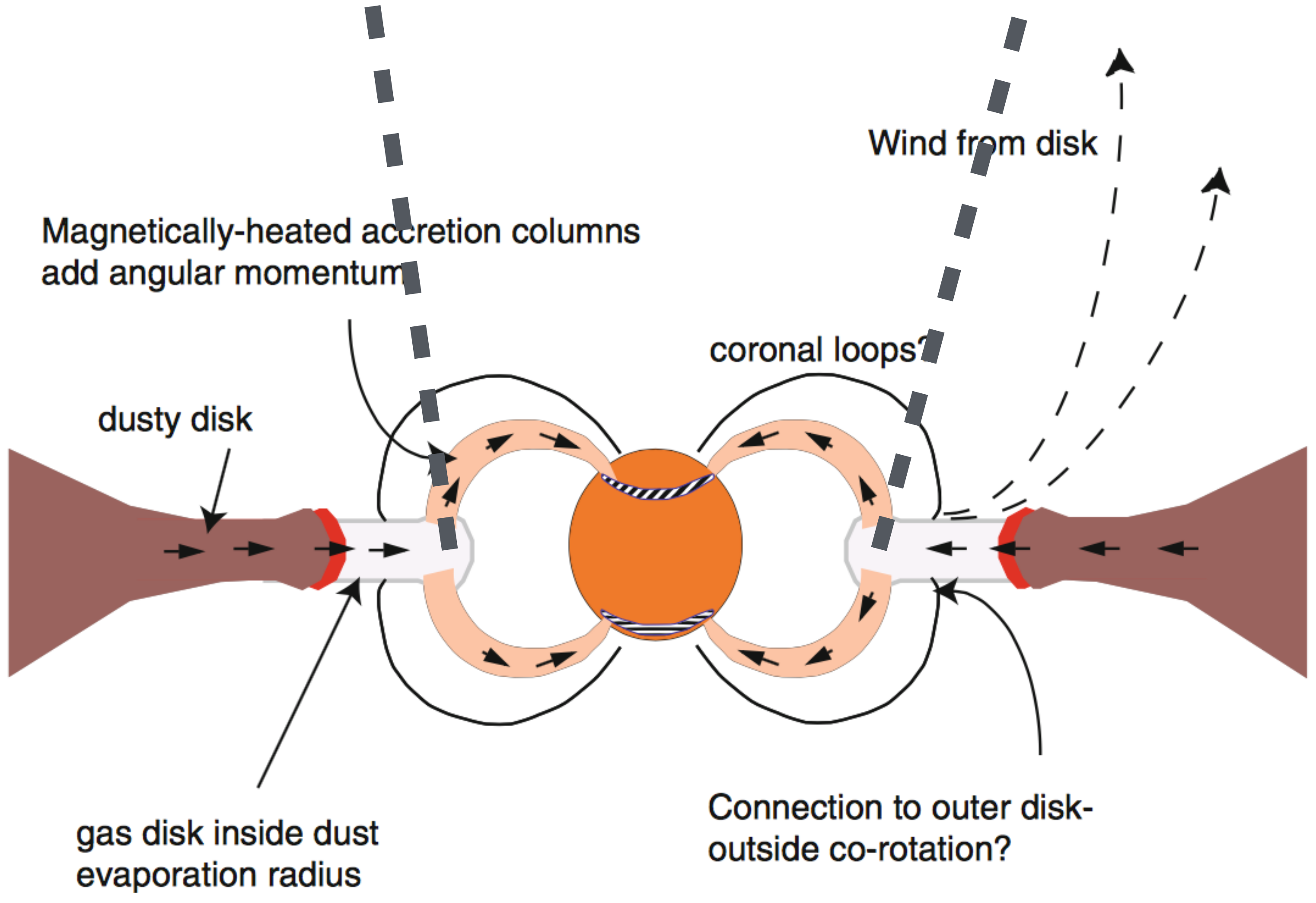
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.01
0.1
1.0
intrinsic
observed
occurrence rate ($R_p = 1-4\ R_\oplus$)
Semi-major axis [au]

G. Mulders



Mulders et al. (2015a)

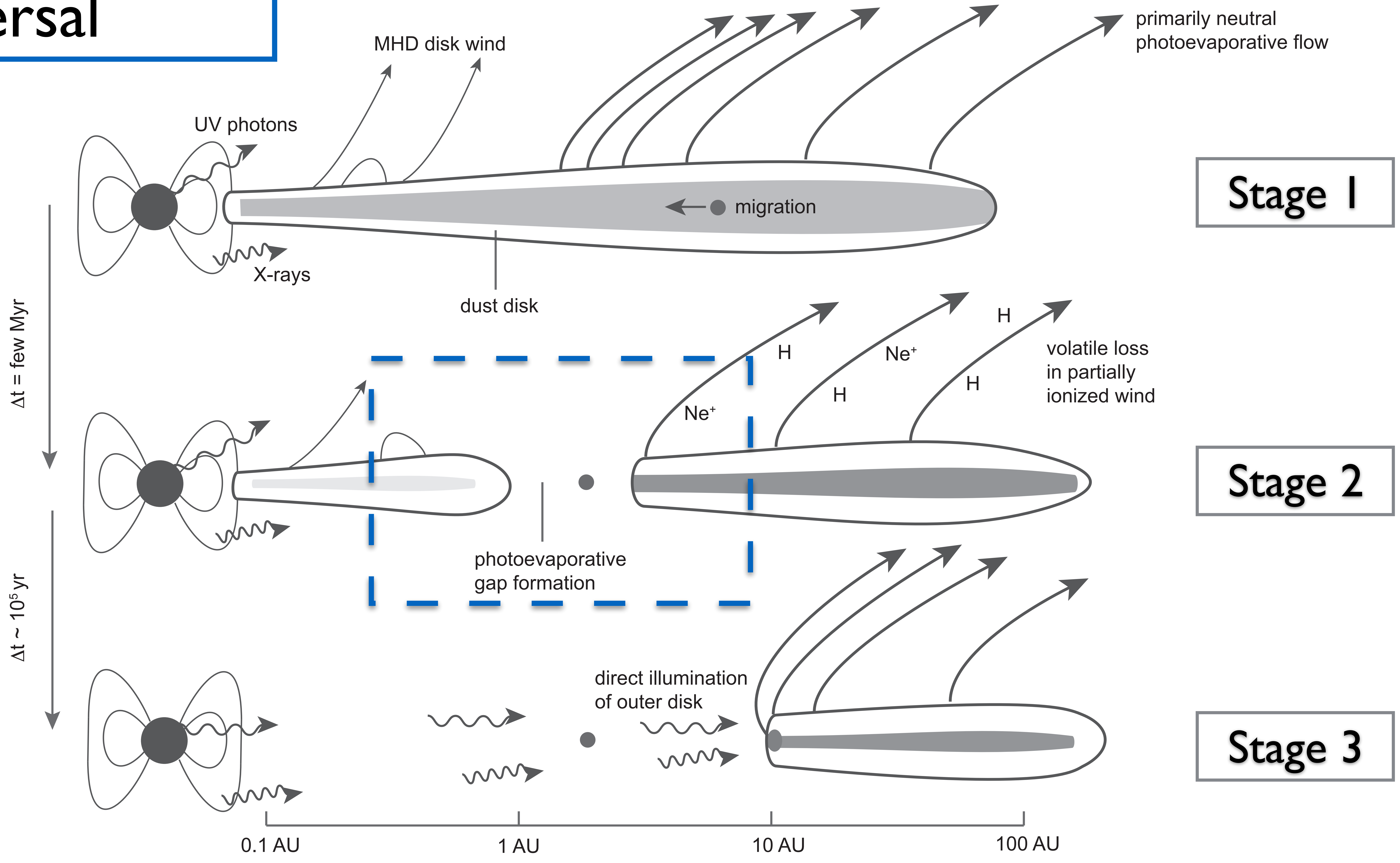
$$a_{turn} \sim (M_{star})^{1/3}$$



The scaling relation between a_{turn} and M_{star} suggests that migration (of fully formed planets and/or their building blocks) shaped the inner architecture of planetary systems

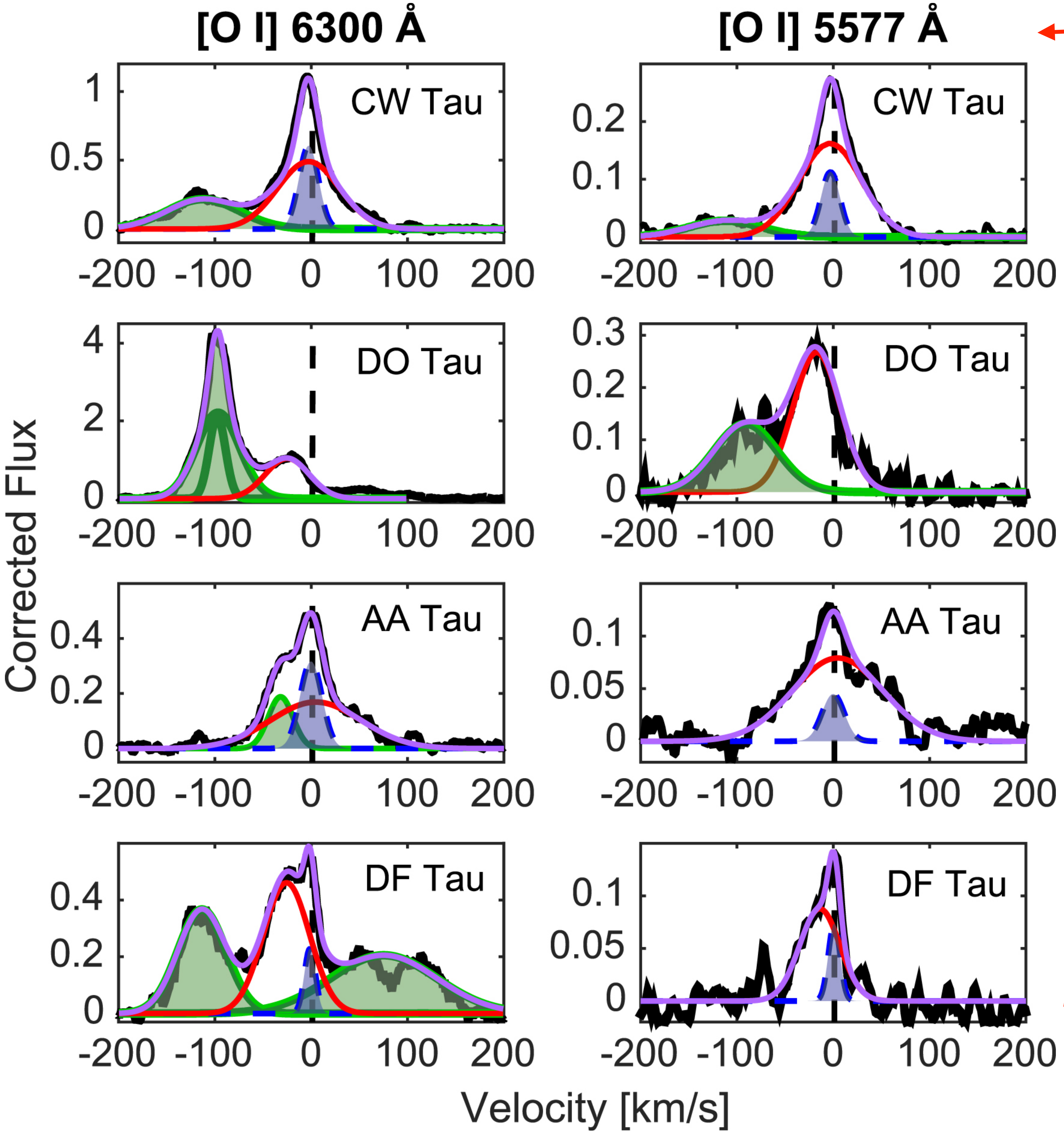
(Lee & Chiang 2017: migration of building blocks)

Stages of disk evolution and dispersal

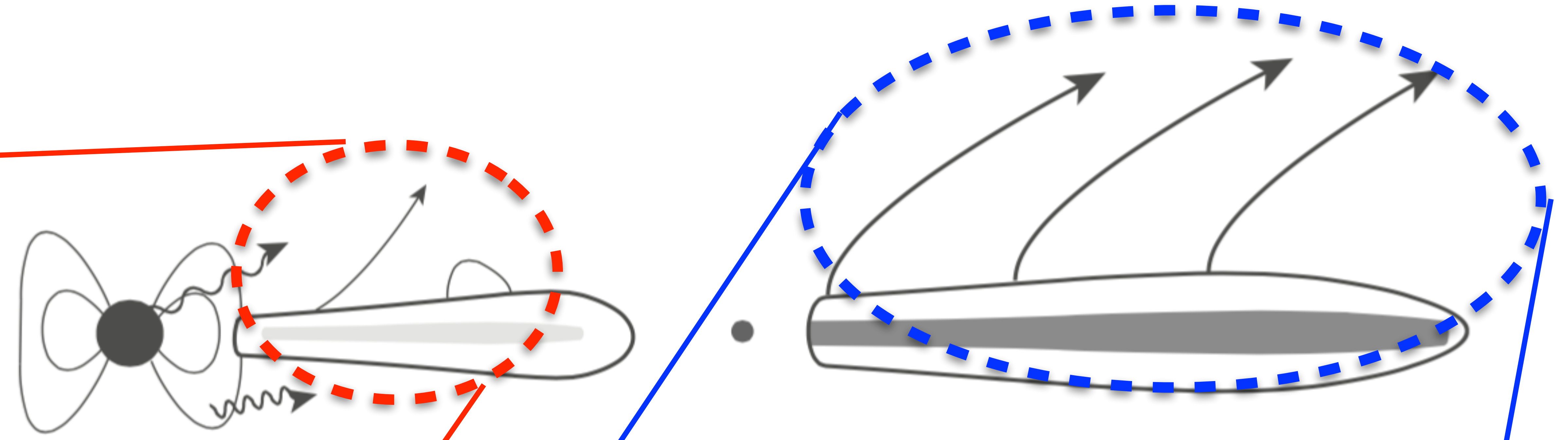


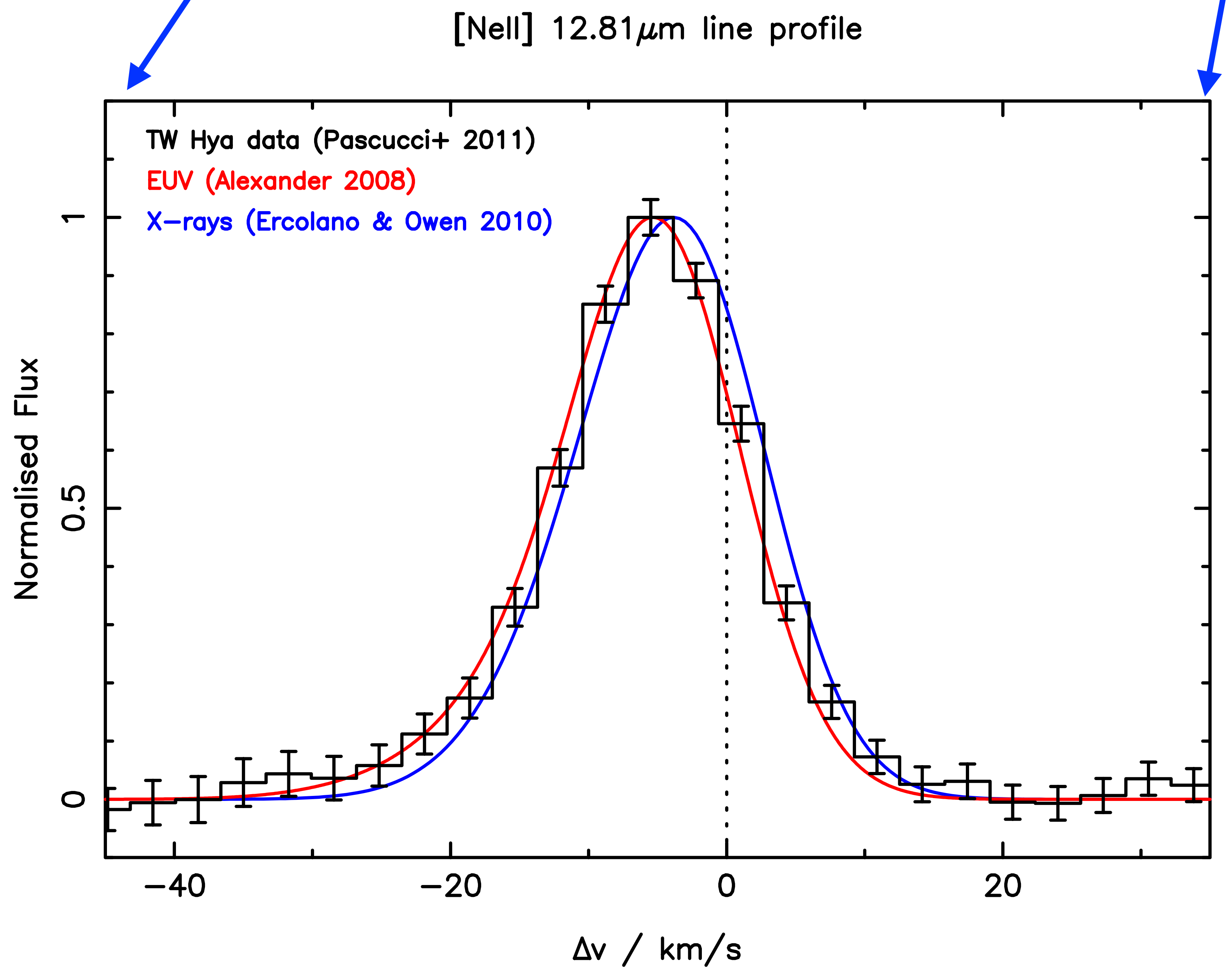
From Alexander, Pascucci et al. 2014 (PPVI review)

Direct evidence of winds = flowing gas from the disk surface



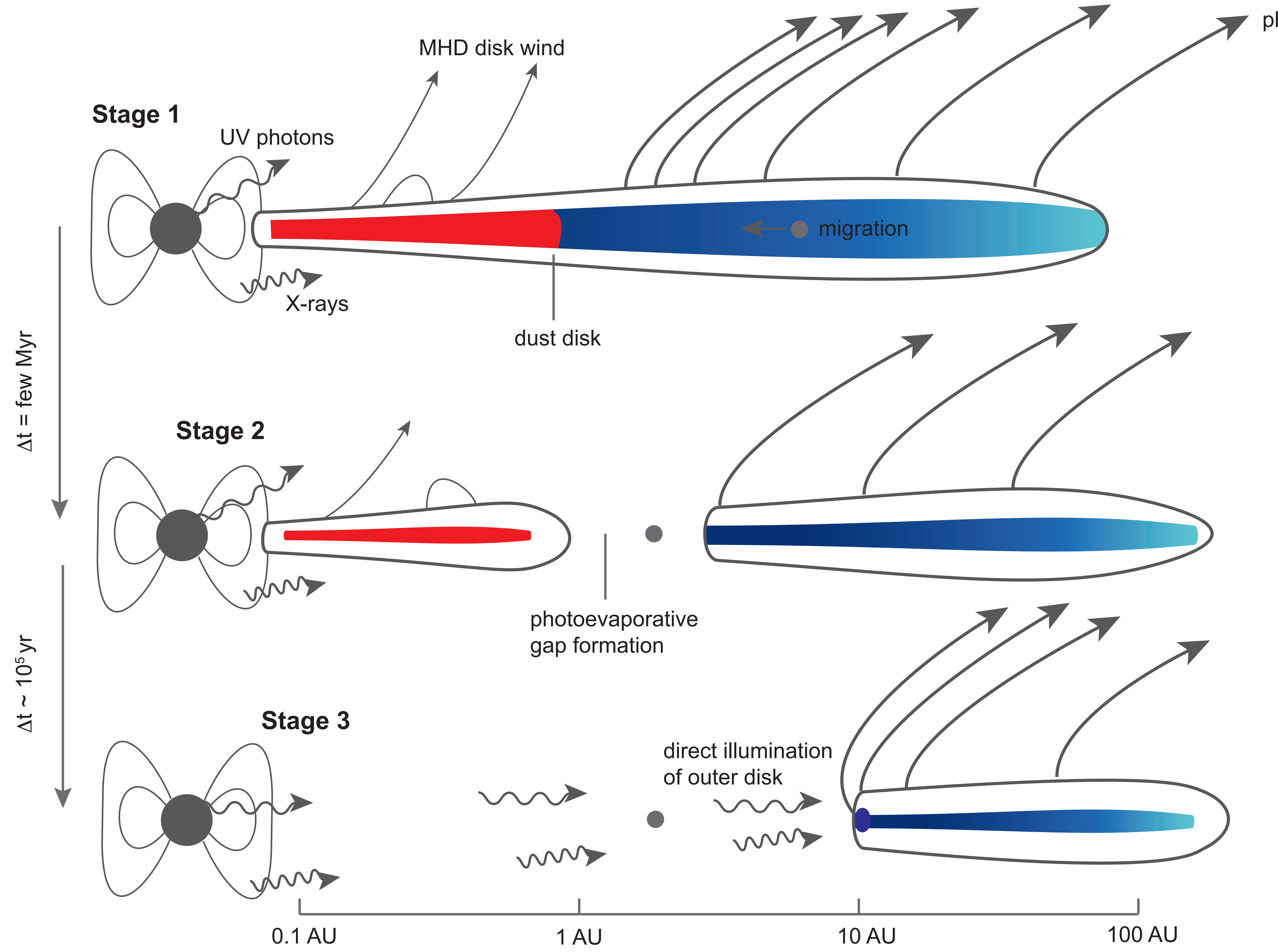
Simon, Pascucci et al. (2016)

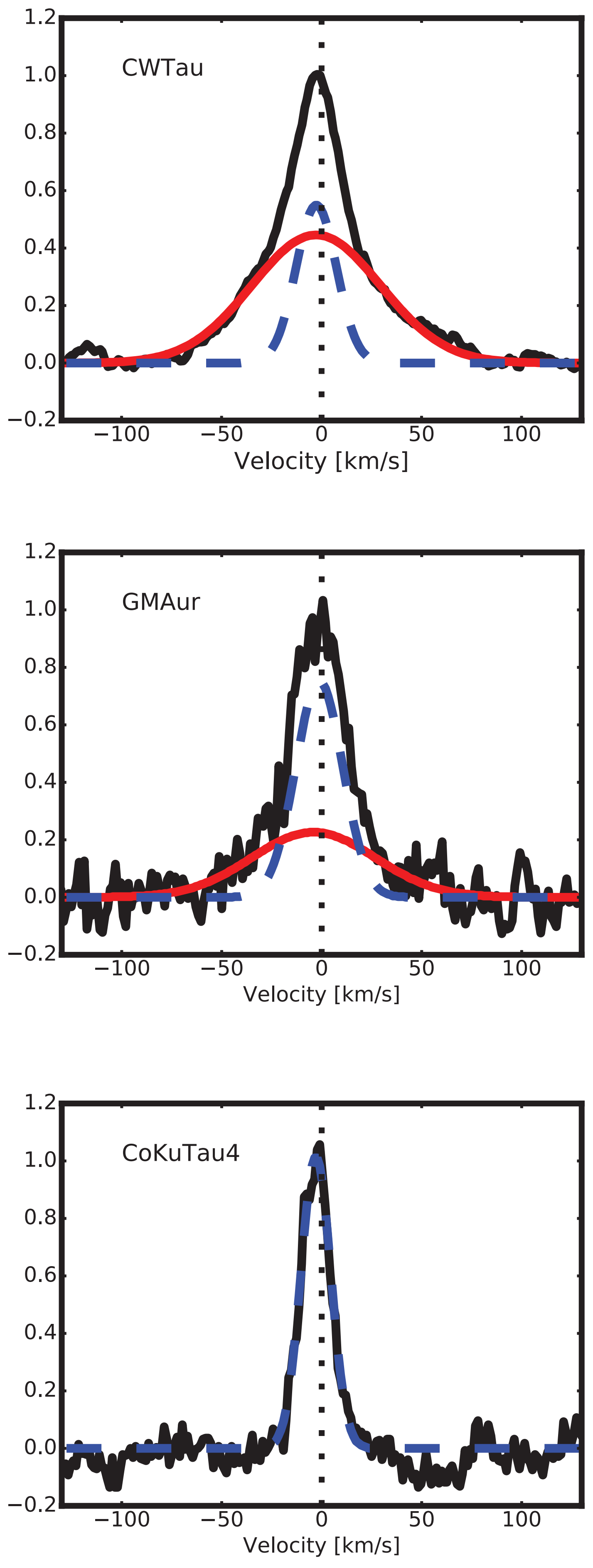




REFs: Pascucci & Sterzik (2009); Pascucci et al. (2011, 2012); Szulágyi et al. (2012); Rigliaco, Pascucci et al. (2013); Pascucci et al. (2014); Simon, Pascucci et al. (2016)

Evolution of disk winds

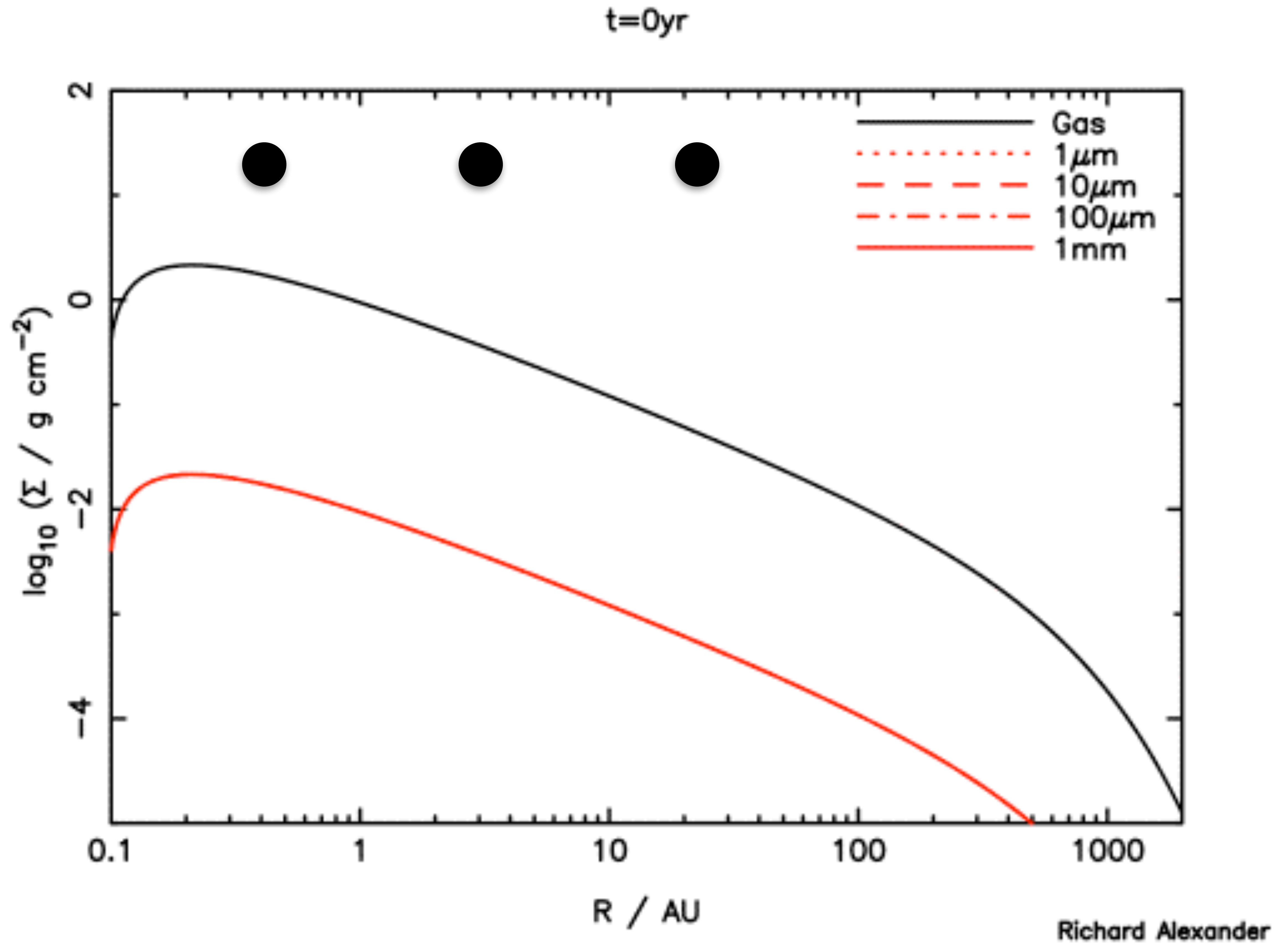


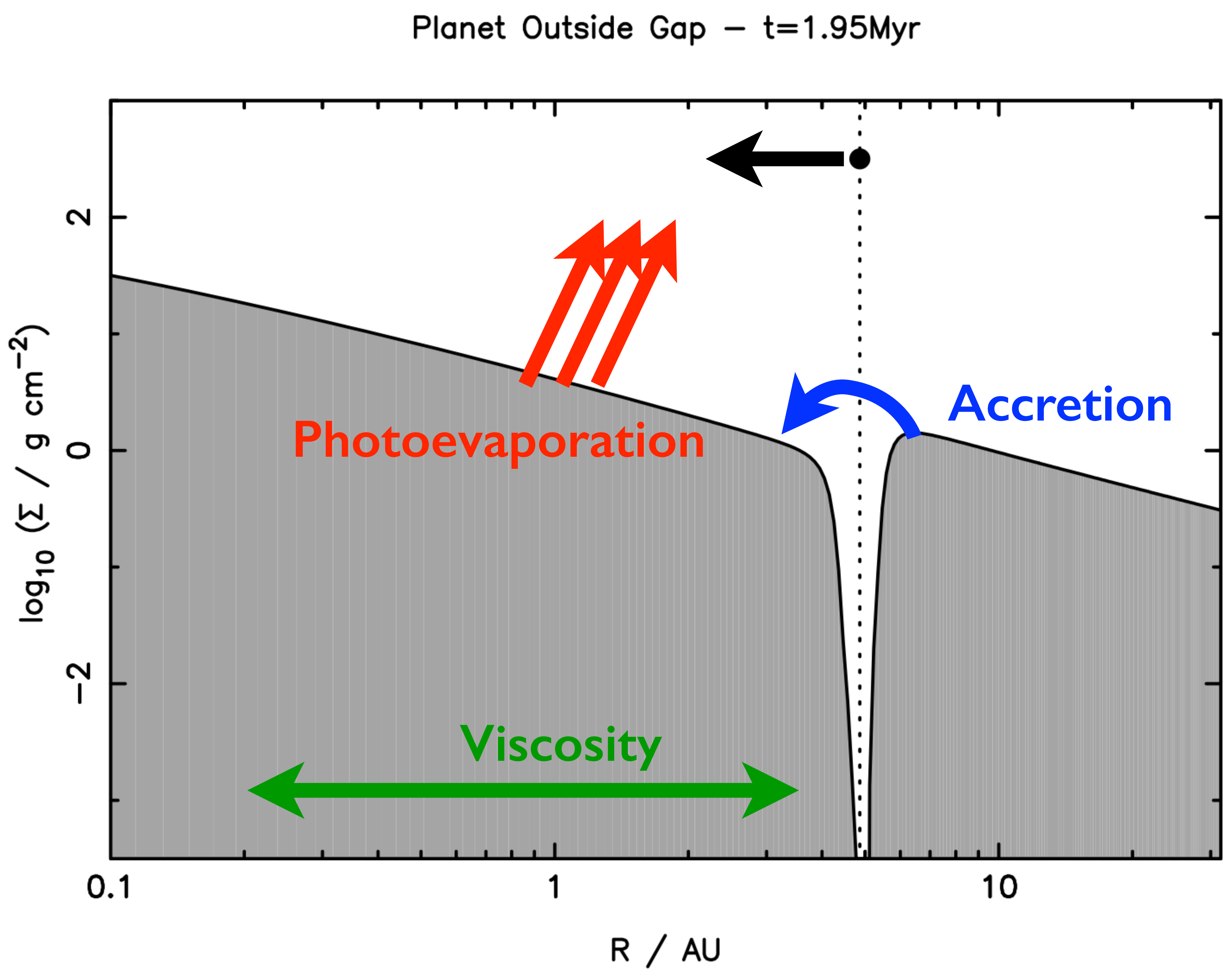


Simon et al. (2016)

From the review article of Ercolano & Pascucci (2017)

Migrating giant planets in dispersing disks

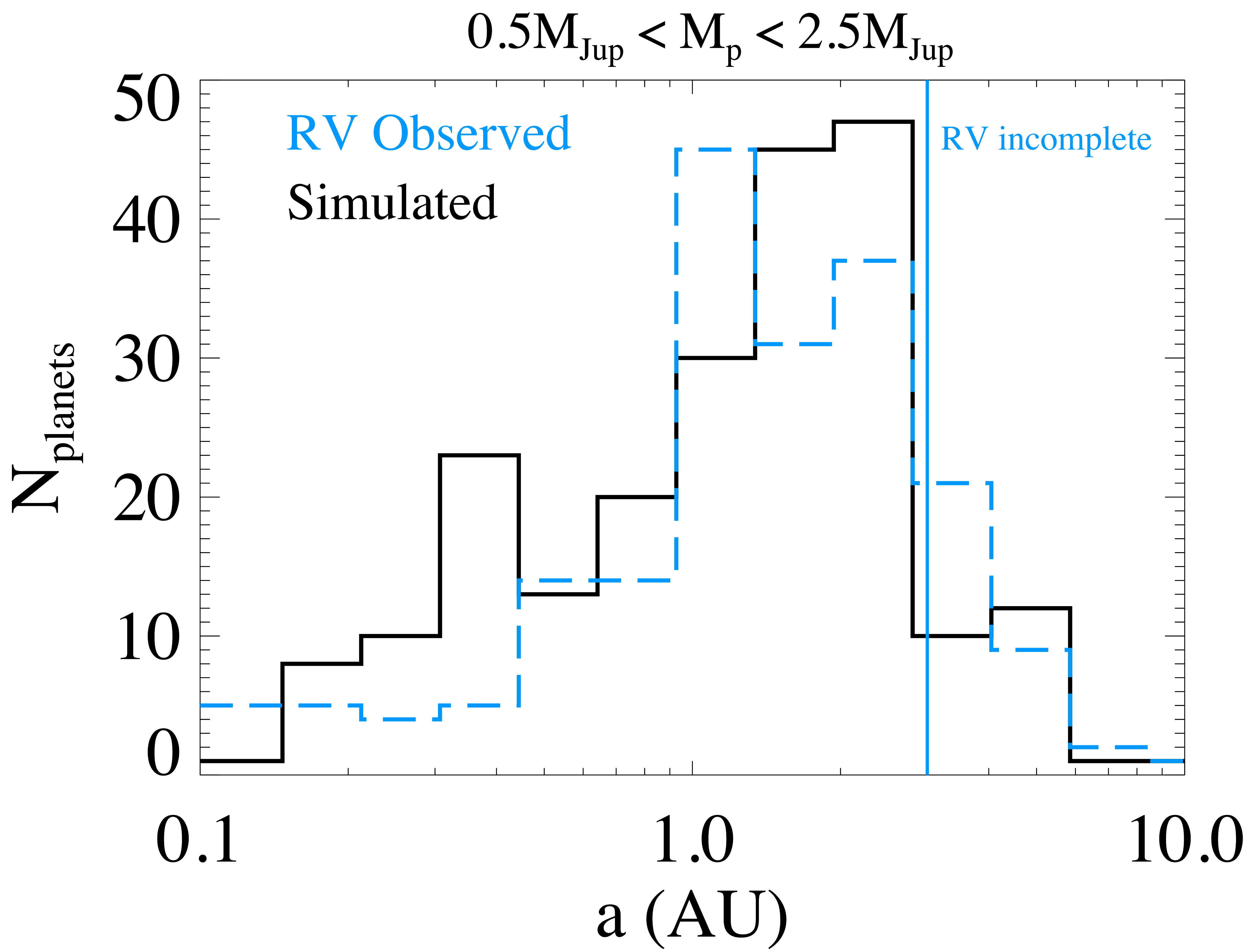




Monte Carlo simulations of planet-disk models with randomly sampled initial conditions (e.g. disk mass; planet mass, location, and time of formation). Alexander & Pascucci (2012).

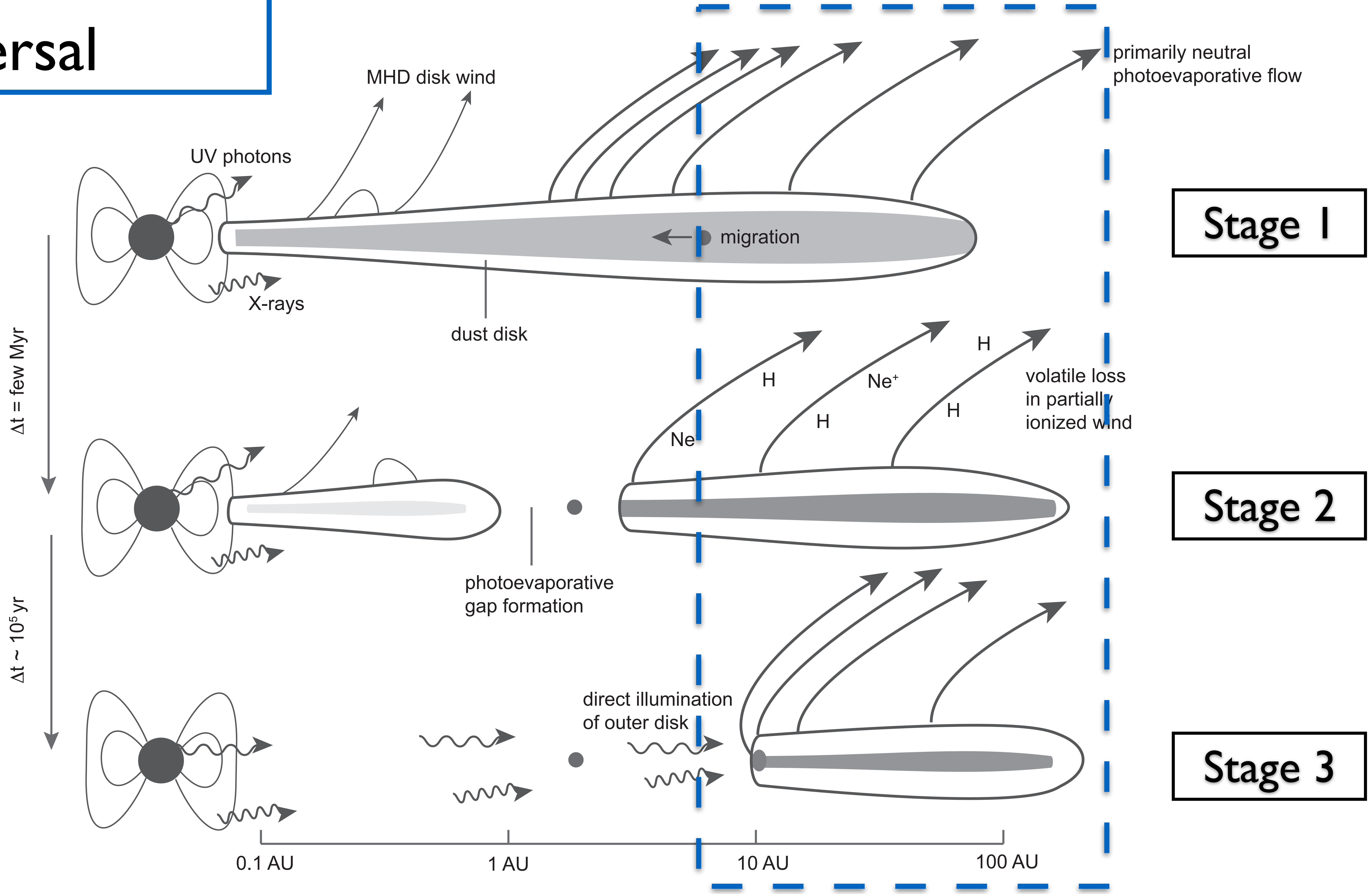
Deserts and pile-ups of giant planets

Scaling relation for the gap:
$R_{crit} \sim M_{star}/c_s^2$



Alexander & Pascucci (2012)

Stages of disk evolution and dispersal



From Alexander, Pascucci et al. 2014 (PPVI review)

The outer disk: disk masses & solids available to form planets

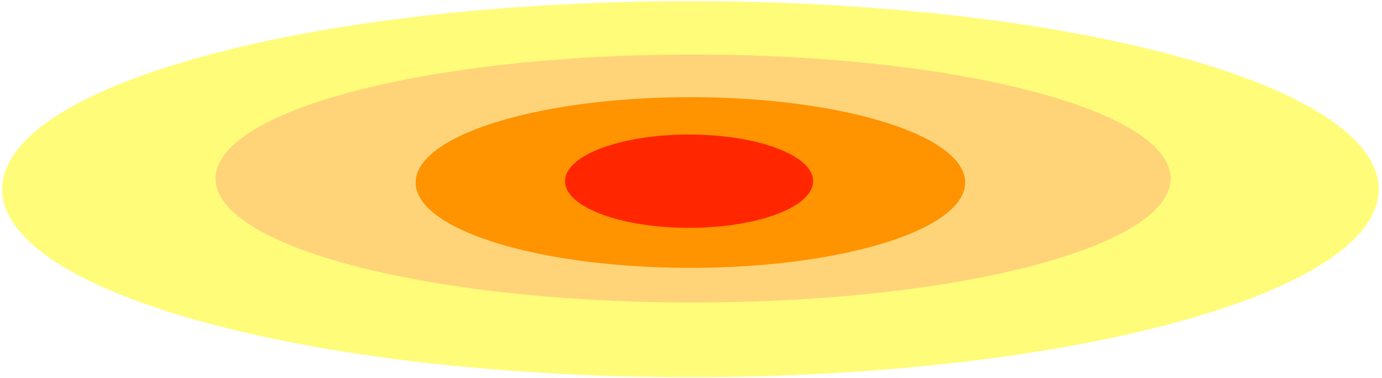
Based on ALMA (I. Pascucci, PI) + VLT/XShooter (Herczeg and Testi, PI) data

Pascucci et al. (2016): "A Steeper than Linear Disk Mass-Stellar Mass Scaling Relation"

Papers: – Pascucci et al. 2016 (dust disk masses) – Hendler, Mulders, Pascucci et al. 2017 (disk outer radius - dust mass scaling relation); – Long, Herczeg, Pascucci et al. 2017 (gas disk masses); – Manara et al. 2017 (stellar and accretion properties); – Mulders, Pascucci et al. 2017 (accretion rates vs disk masses)

Optically thin dust emission in the mm → Disk mass

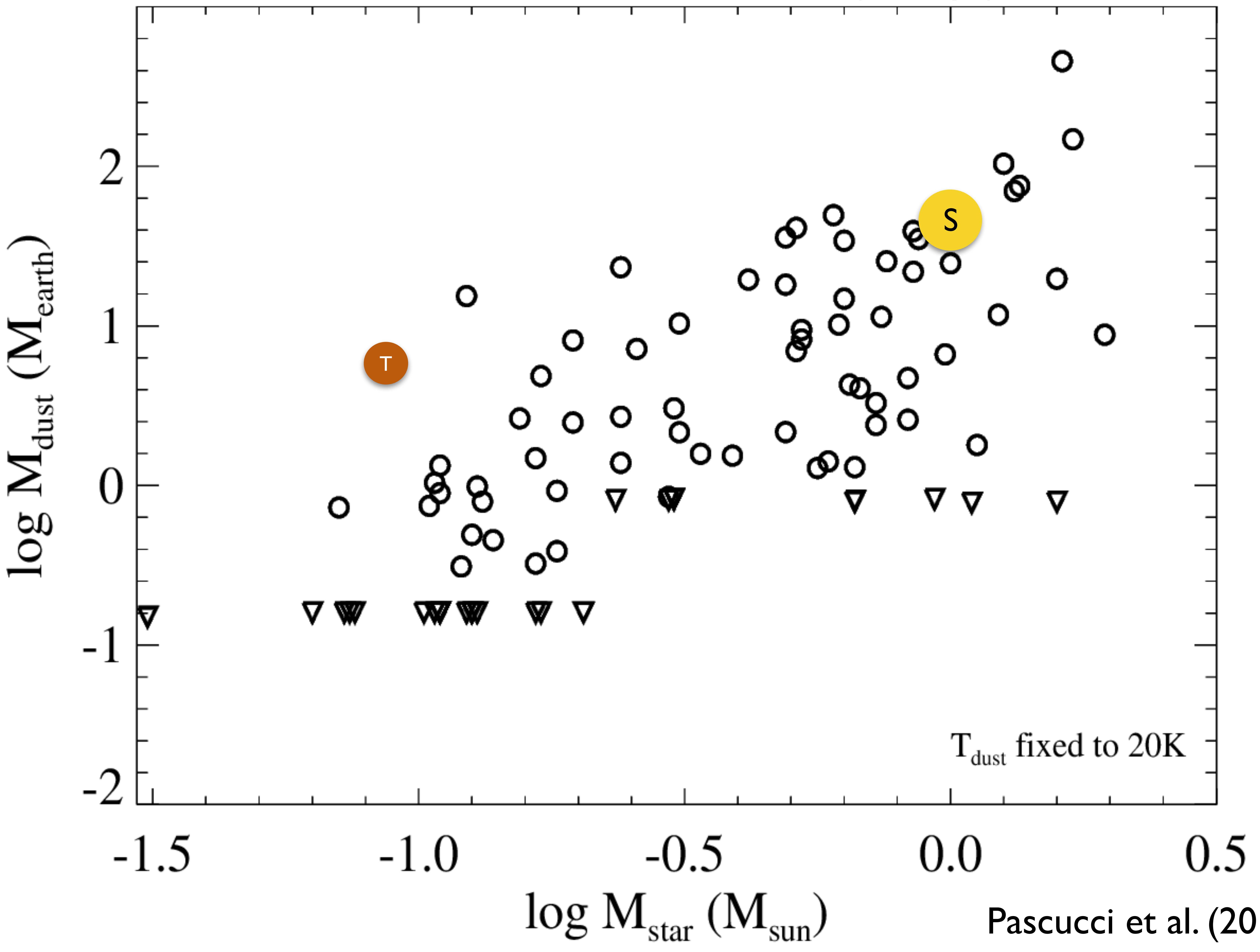
$$F_\upsilon = \frac{\cos\theta}{d^2}\int_{Rin}^{Rout} B_\upsilon(T_d)(1-e^{-\tau_\upsilon})2\pi R dR$$



$$\tau_\upsilon = \frac{\kappa_\upsilon \Sigma}{\cos\theta}$$

$$if\, \tau_\upsilon < 1 \quad \longrightarrow \quad F_\upsilon = \frac{B_\upsilon(T_d)}{d^2}\kappa_\upsilon M_{dust}$$

Dust disk masses in Chamaeleon I (2-3Myr)

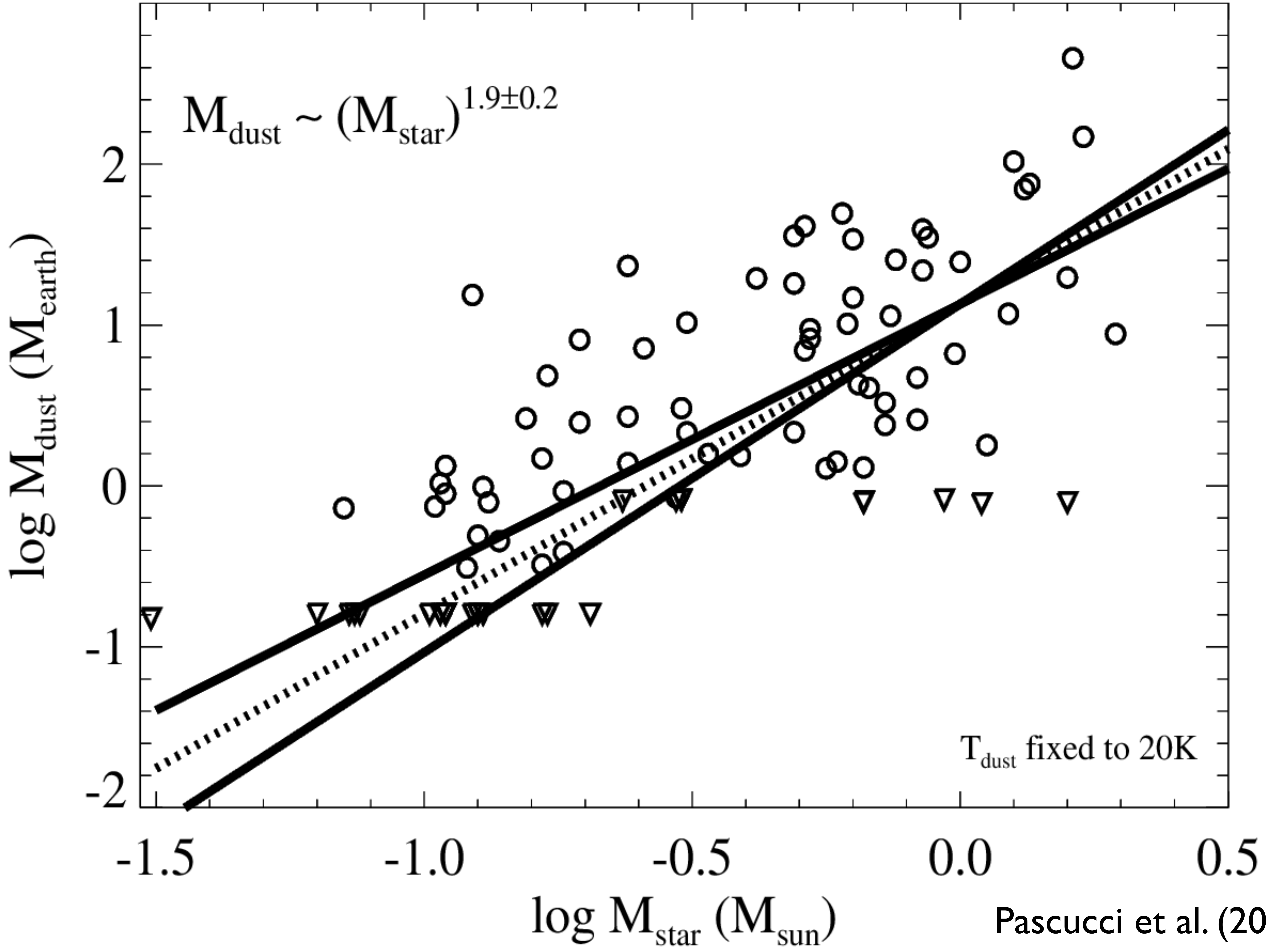


S Solar System

T TRAPPIST-1: Seven Earth-size planets orbiting a 0.08 solar mass star (Gillon et al. 2017)

Pascucci et al. (2016)

Dust disk masses in Chamaeleon I (2-3Myr)



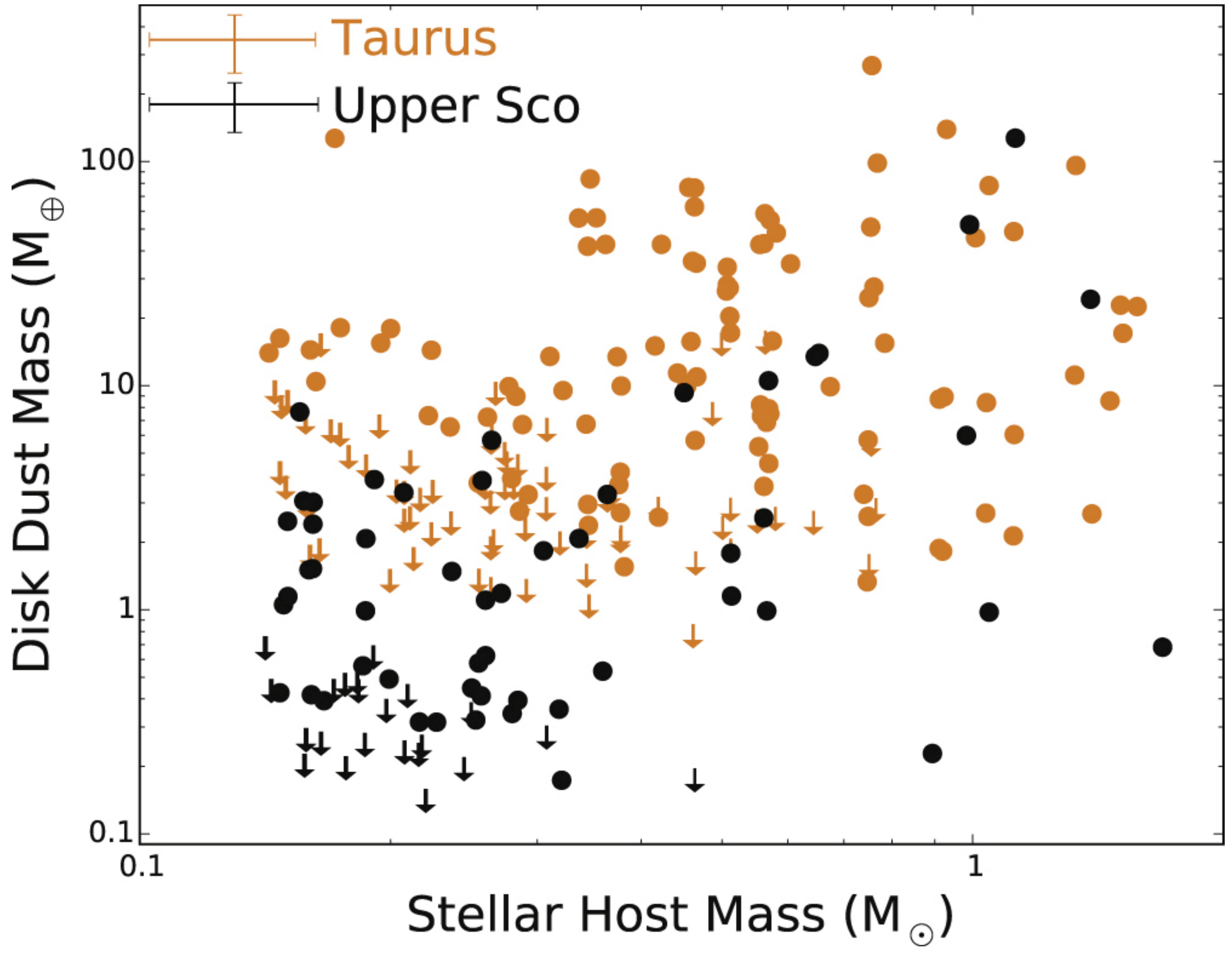
Pascucci et al. (2016)

The relevance of the disk outer radius on T_{dust} is discussed in

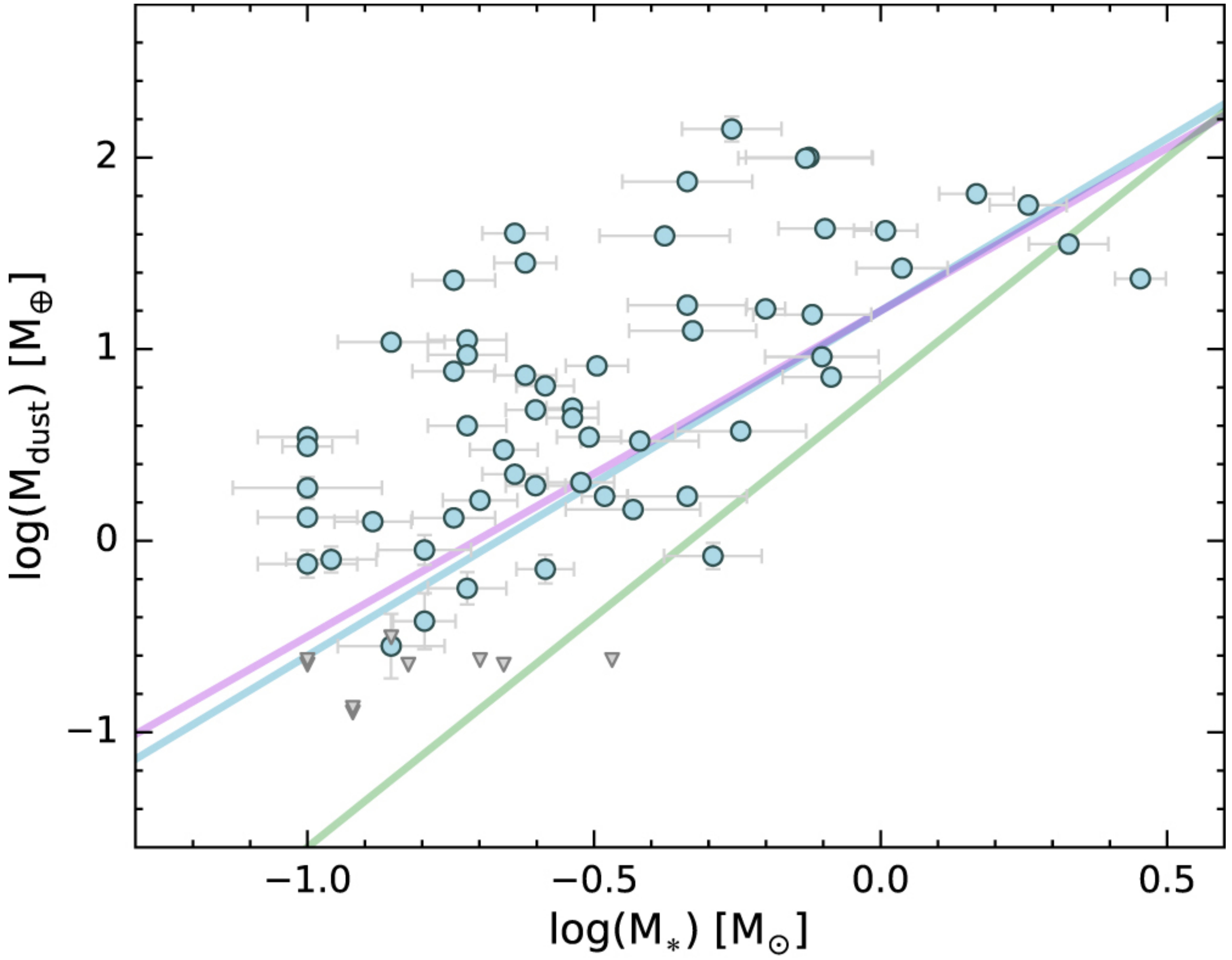
Hendler, Mulders, Pascucci et al. (2017)

USco: Barenfeld et al. (2016)

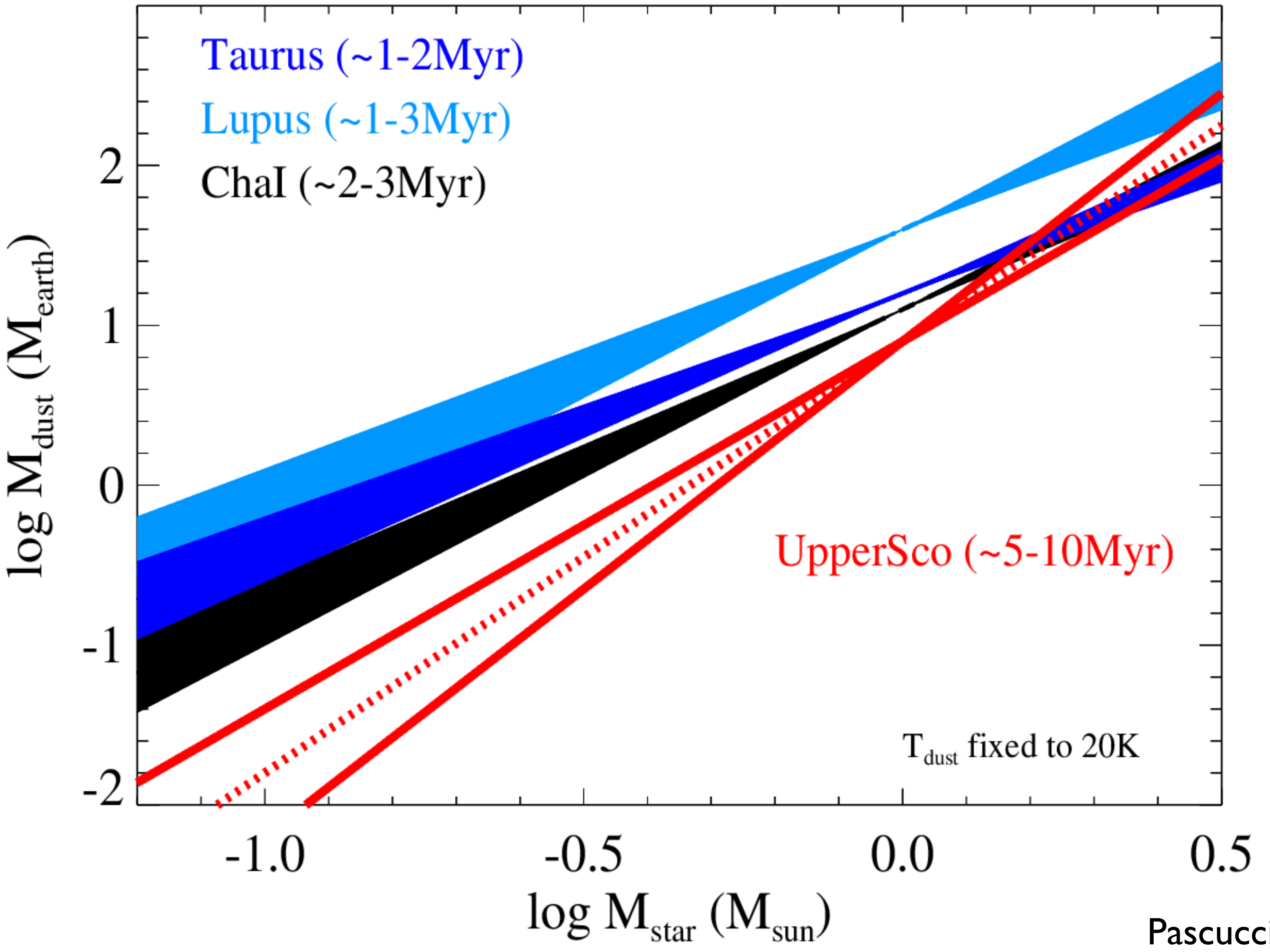
Taurus: Andrews et al. (2013)



Lupus: Ansdell et al. (2016)

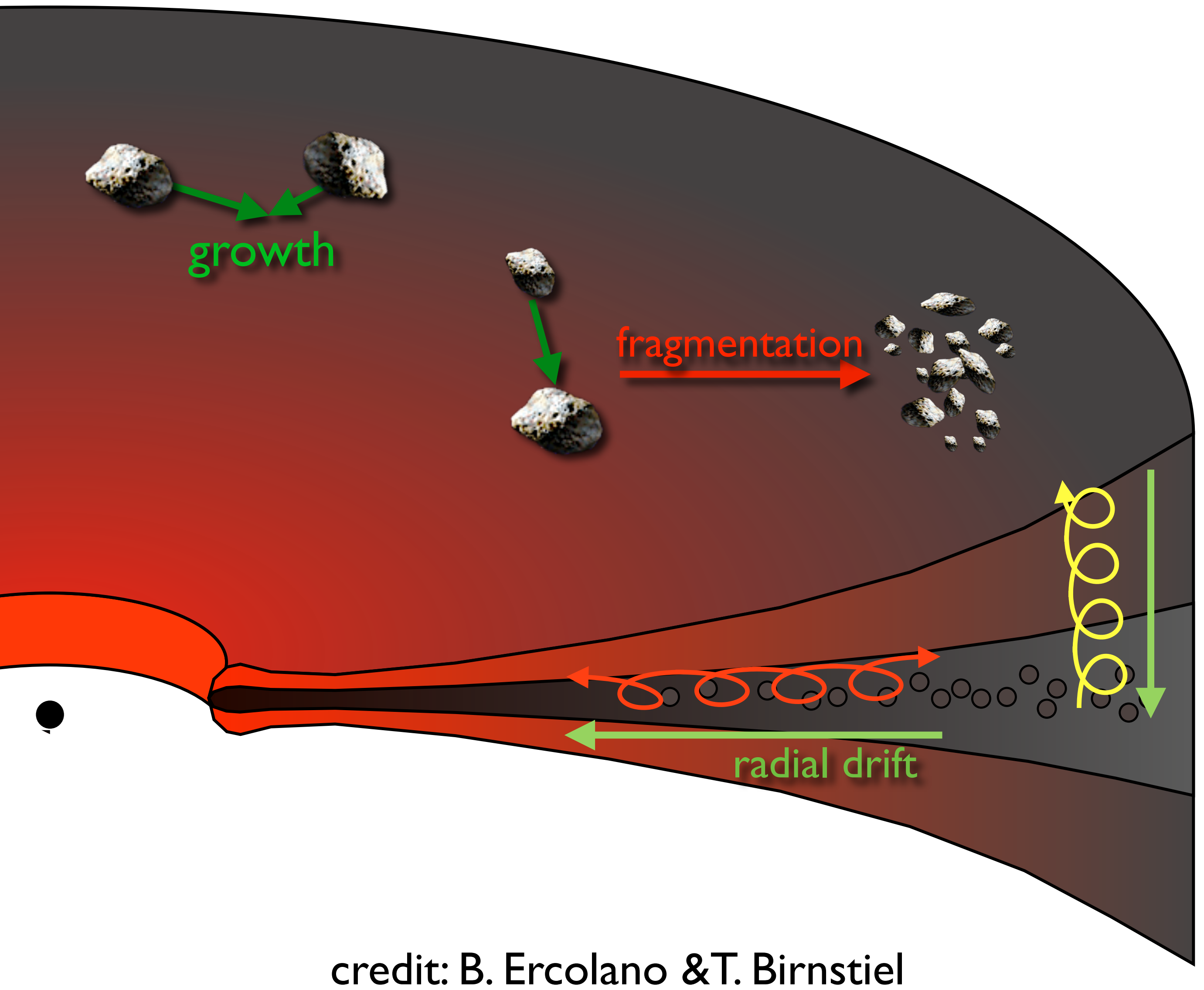


Evolution of dust disk masses



The disk–stellar mass relation steepens with time

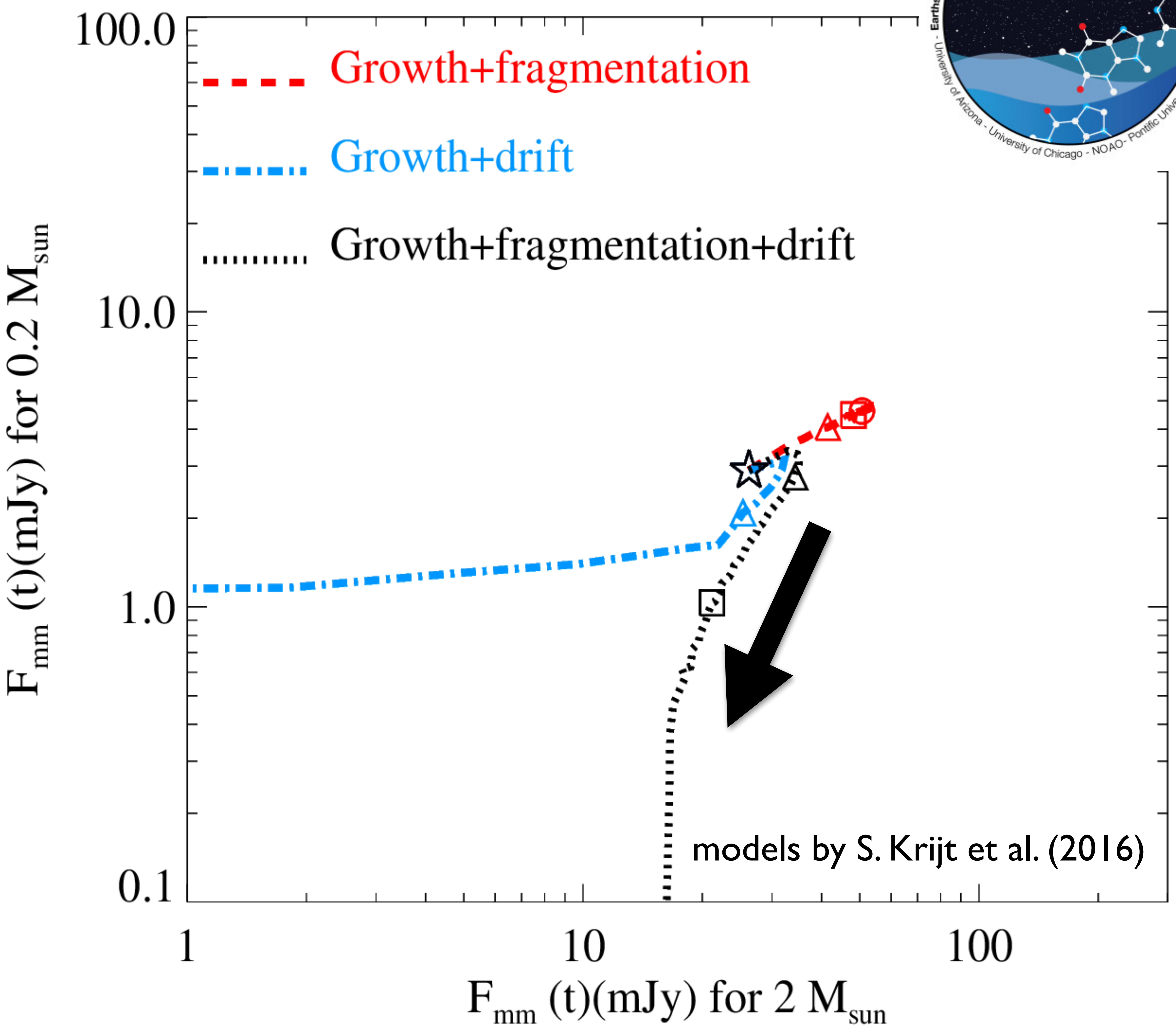
Pascucci et al. (2016)



credit: B. Ercolano &T. Birnstiel

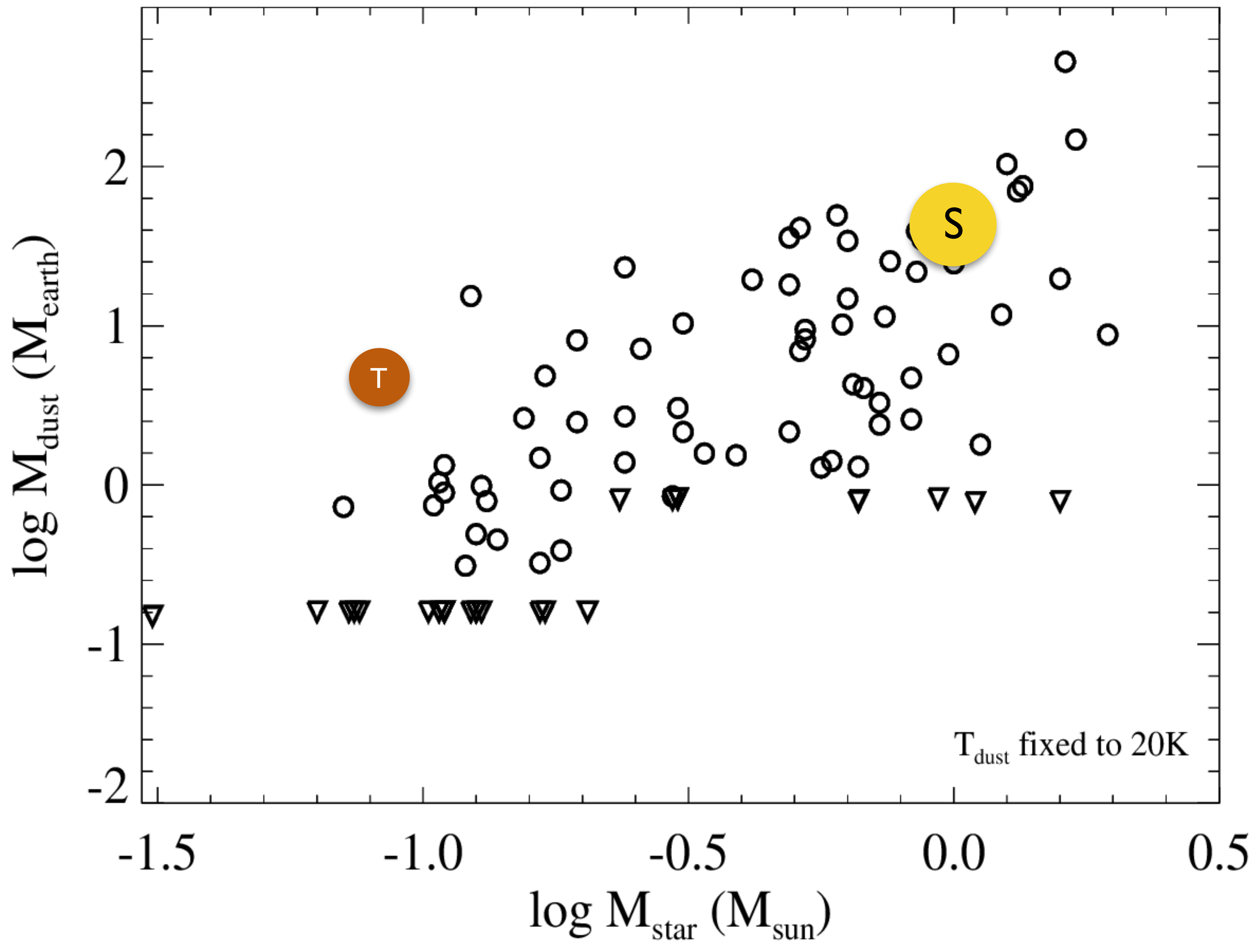
The time for radial drift to remove the largest grains is faster around lower mass stars

Implication: dust disks around lower mass stars are smaller than those around higher mass stars

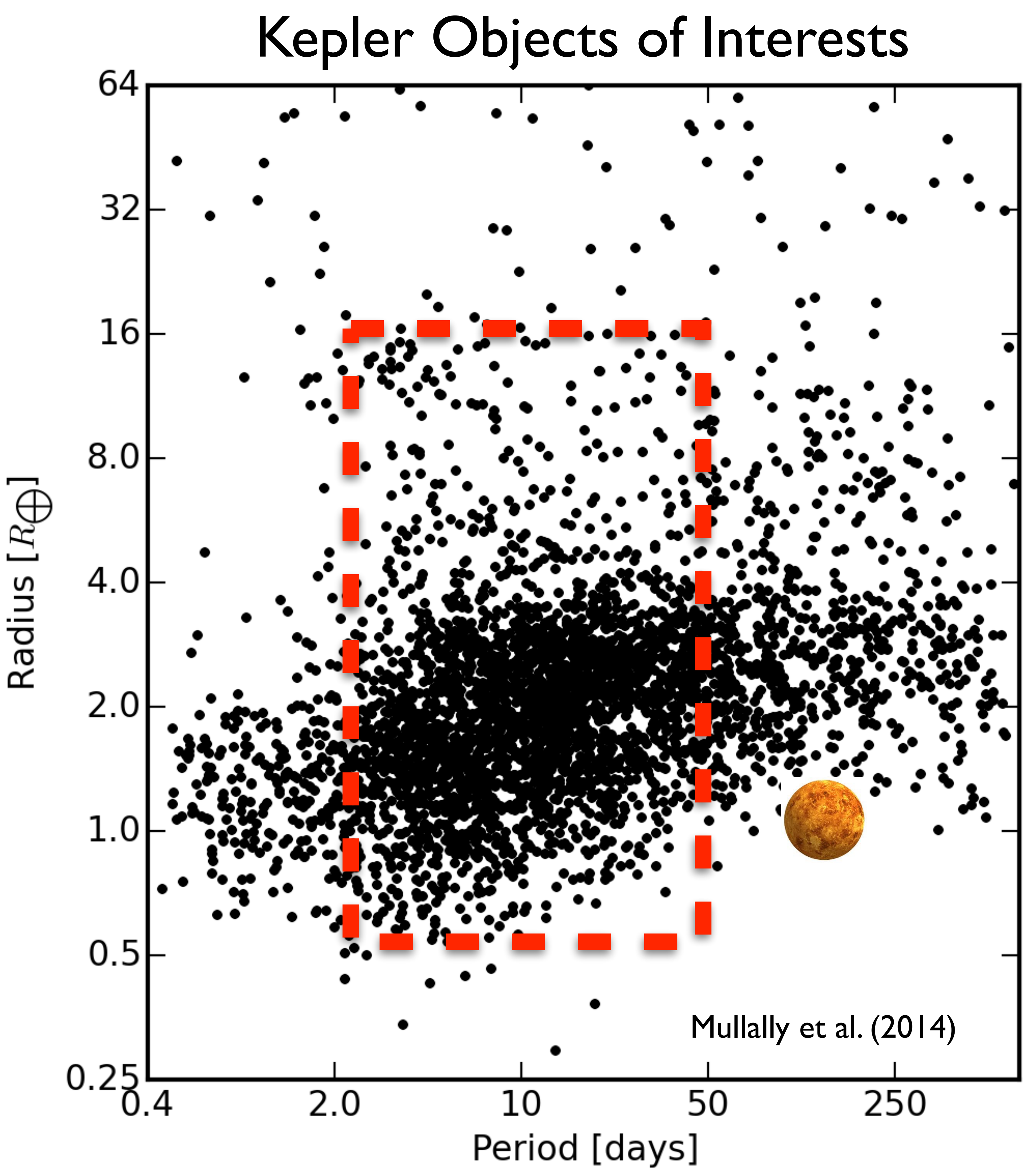


How dust disk masses compare to the distribution of solids in planetary systems?

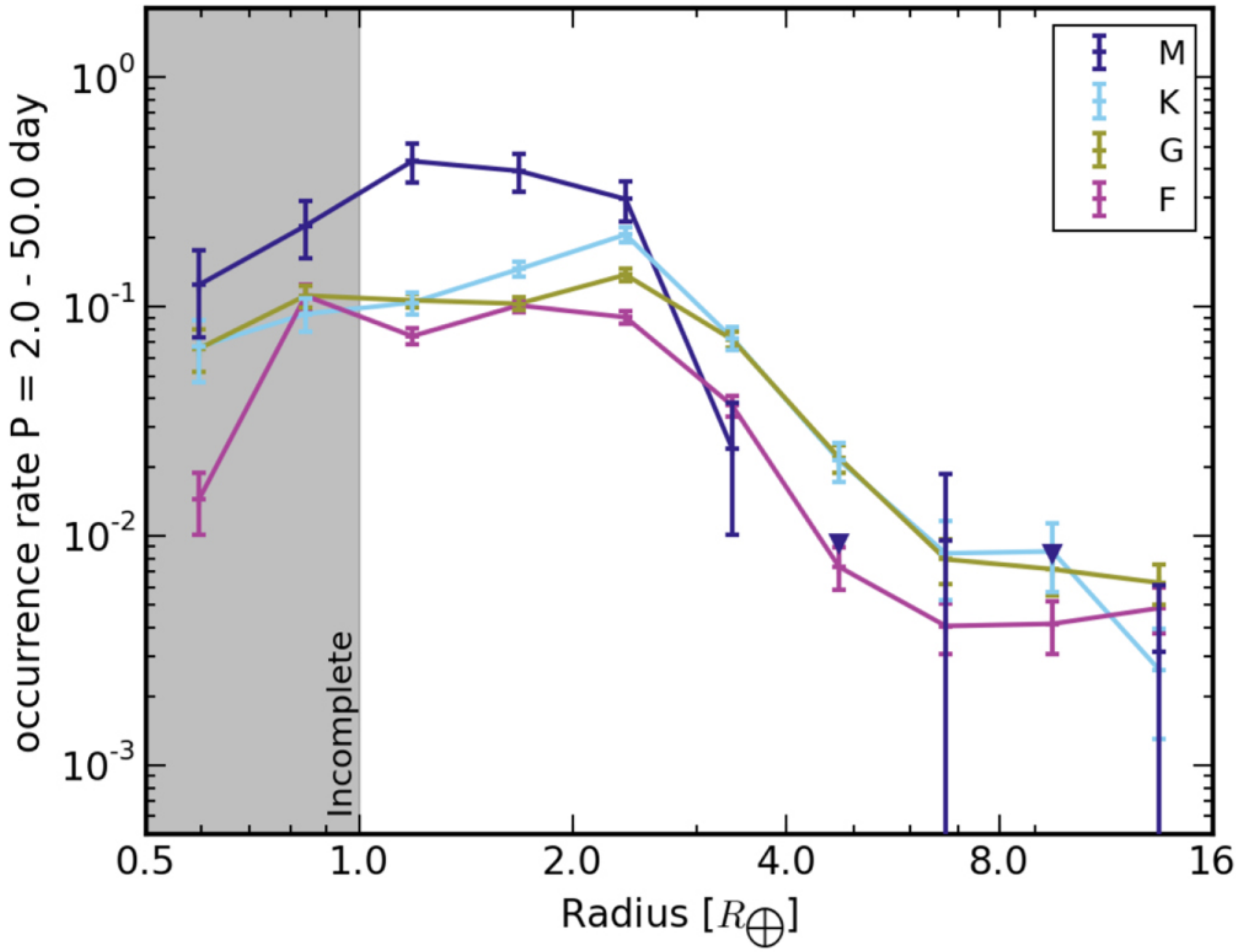
Dust disk masses in Chamaeleon I (2-3Myr)



Pascucci et al. (2016)

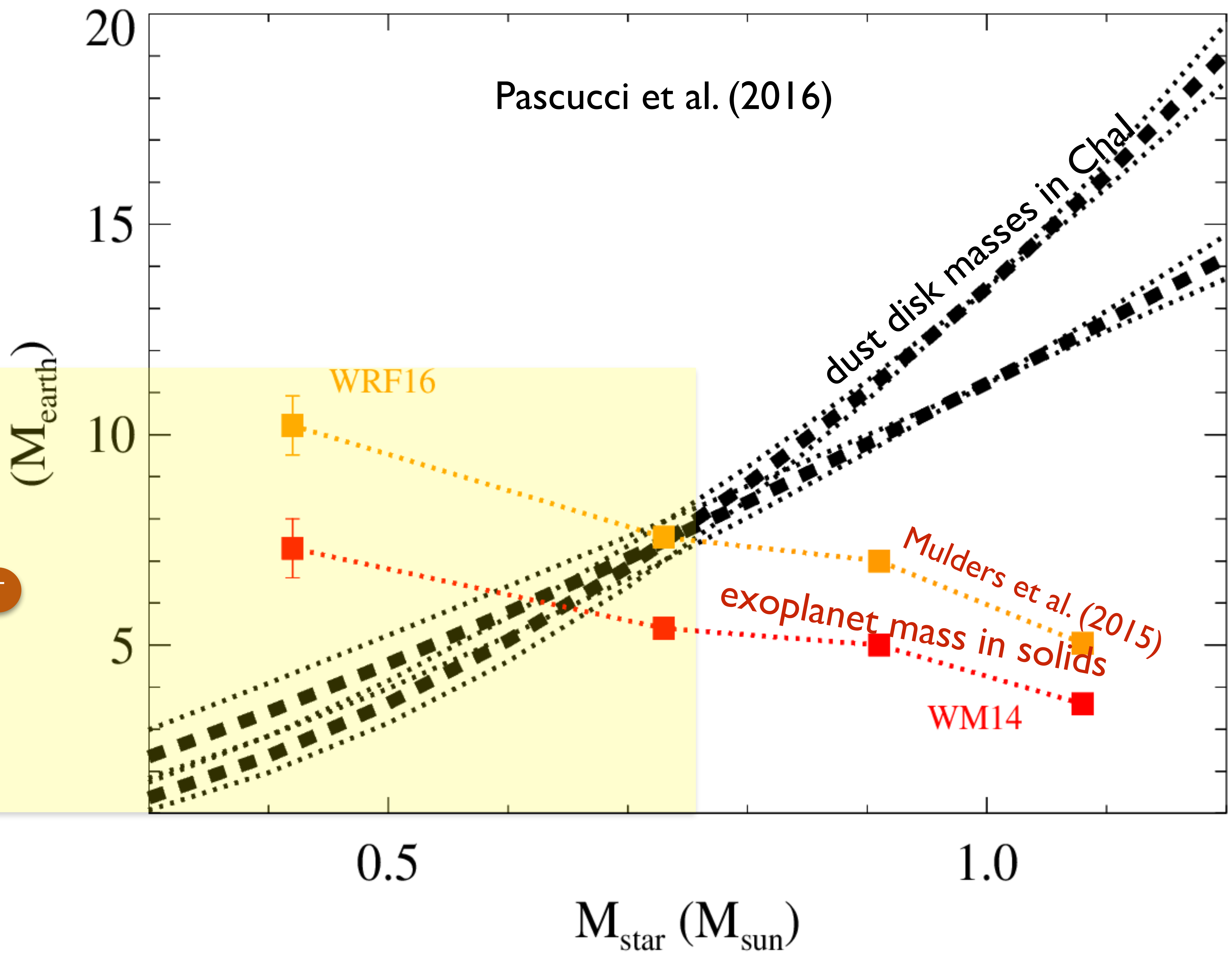


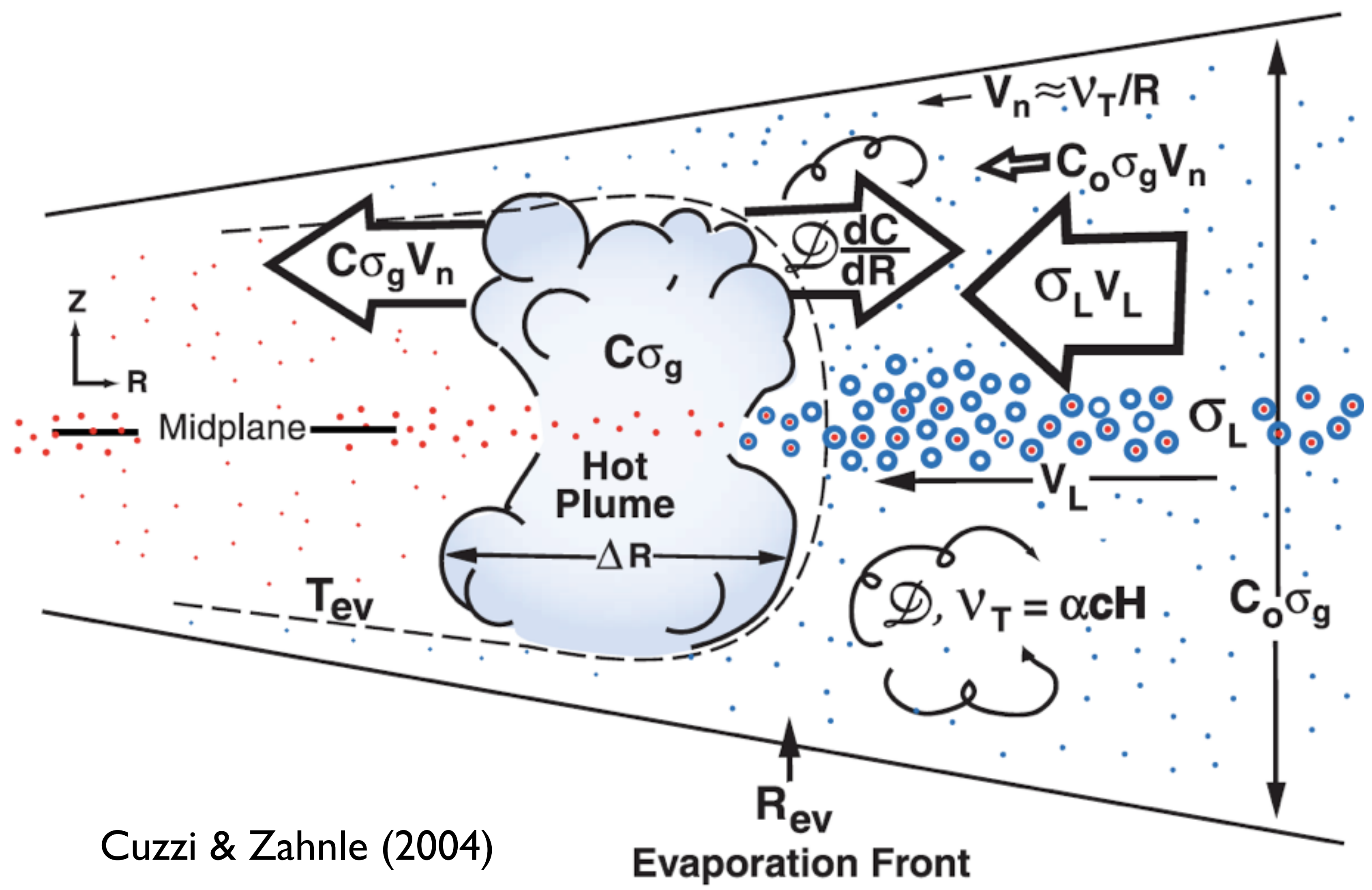
M dwarfs have 3.5 times more 1-2.8R_E planets than FGK stars (but two times less Neptune-size planets)



Mulders et al. (2015b)

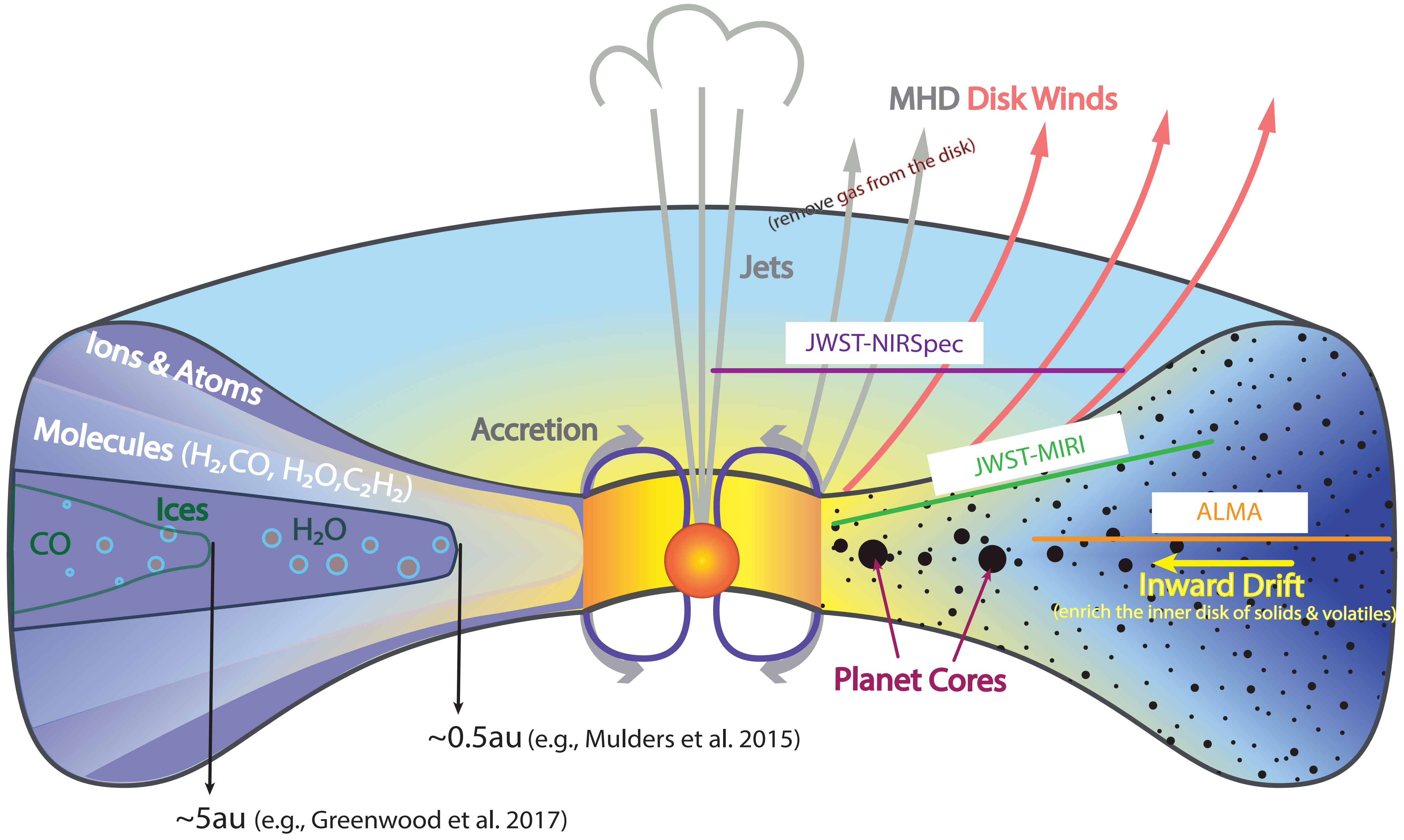
The paucity of pebbles in ~2Myr-old disks around low-mass stars is most likely due to faster inward migration (lack of giants?) toward the star





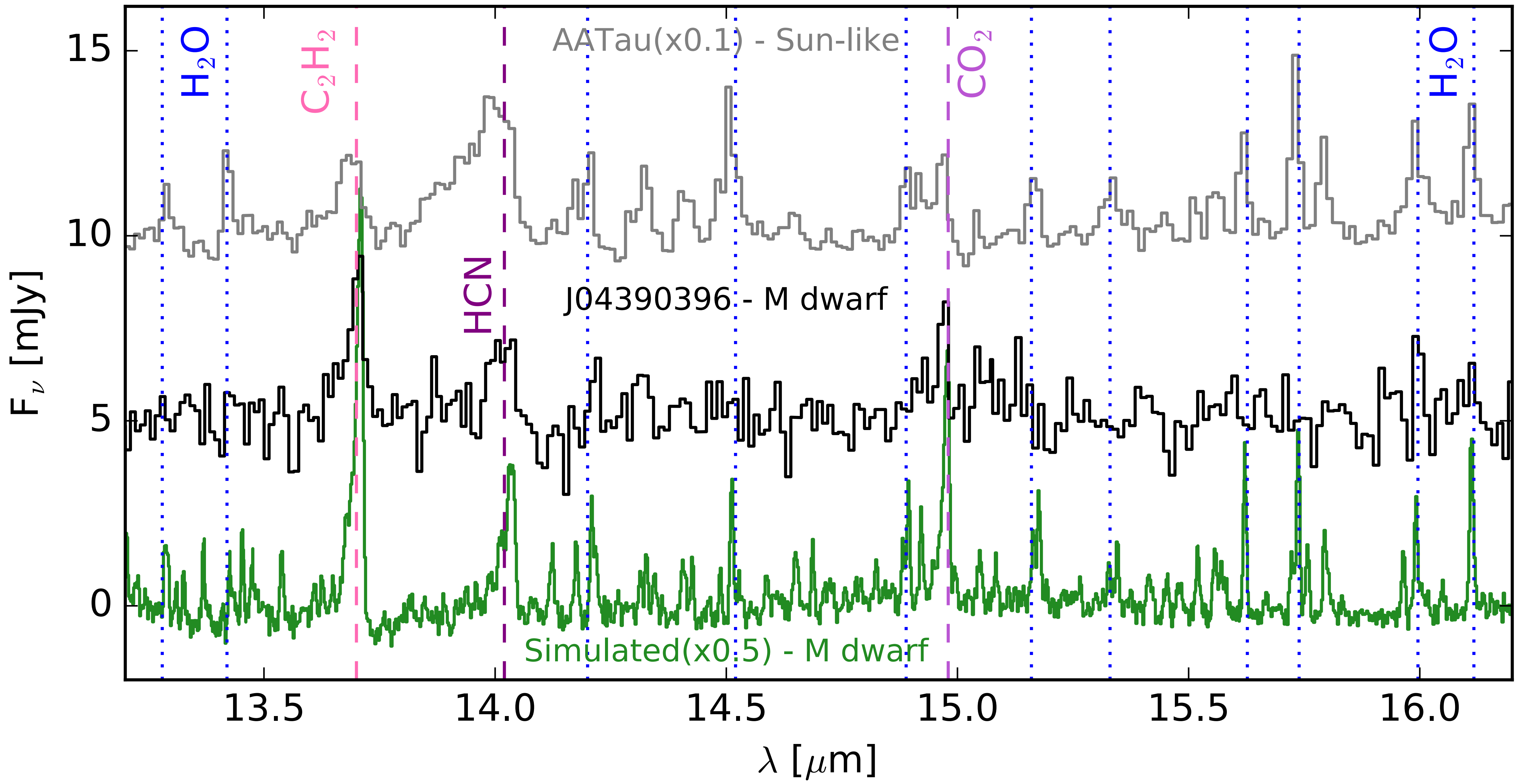
Cuzzi & Zahnle (2004)

The chemistry and dynamics of planet formation around low-mass stars



adapted from Cleeves (2015)

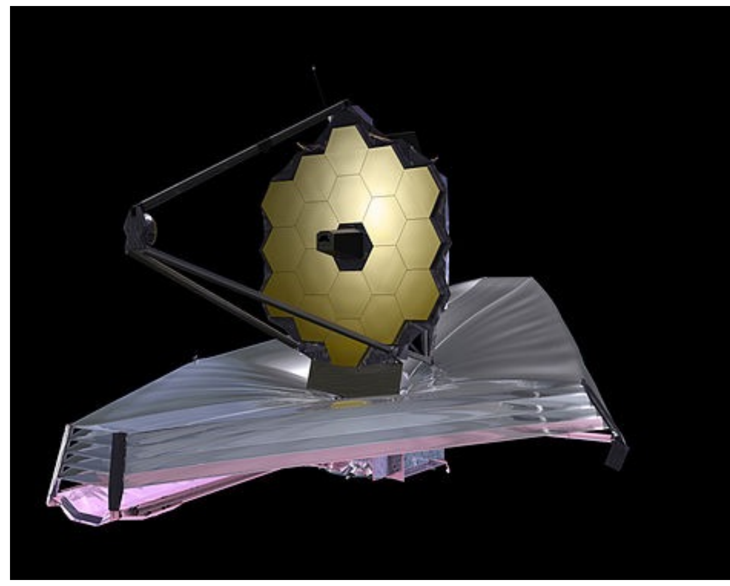
JWST science case: detect volatiles released inside the snowline of disks around low-mass dwarfs. Exo-planetary systems around M dwarfs will be soon discovered by TESS



Carr & Najita (2008)

Pascucci et al. (2013)

RADLite (Pontoppidan et al. 2009)



Which disk properties remain imprinted in the exoplanet population?

Sharp edges, gaps

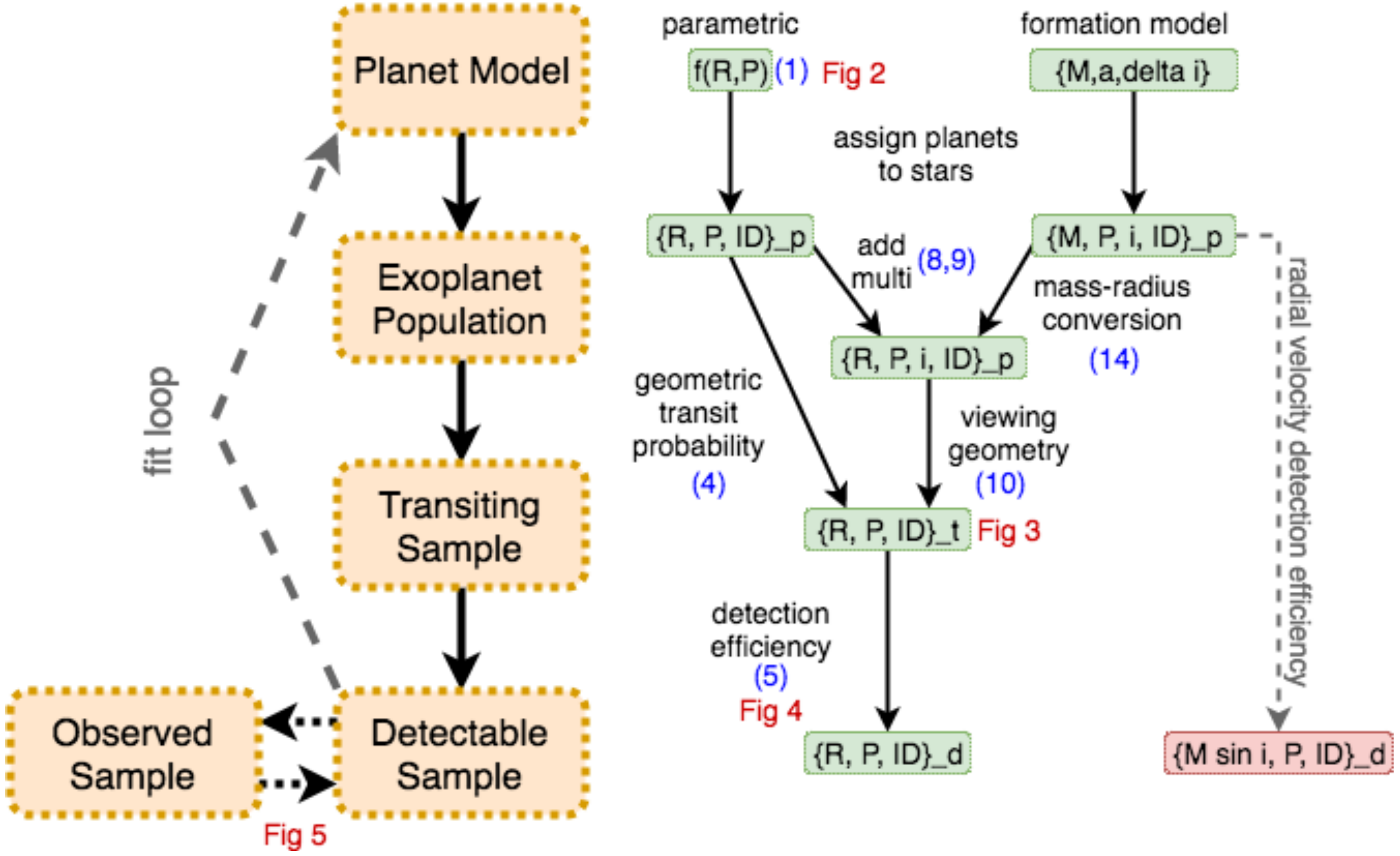
Which physical processes shape planetary systems?

Disk winds, migration of solids

Are there scaling laws in disks and exoplanets?

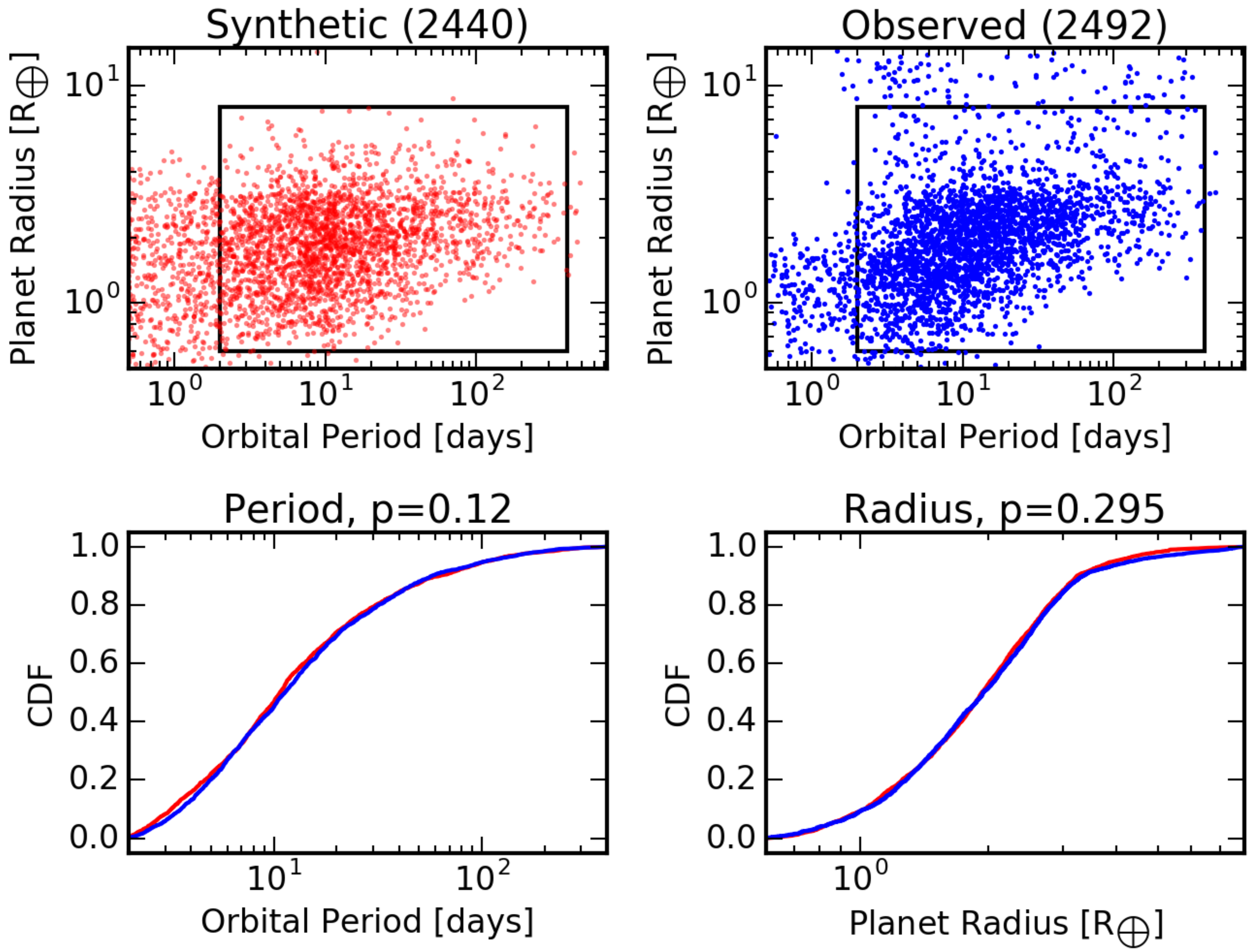
Several scaling relations with stellar mass

EPOS – The Exoplanet Population Observation Simulator

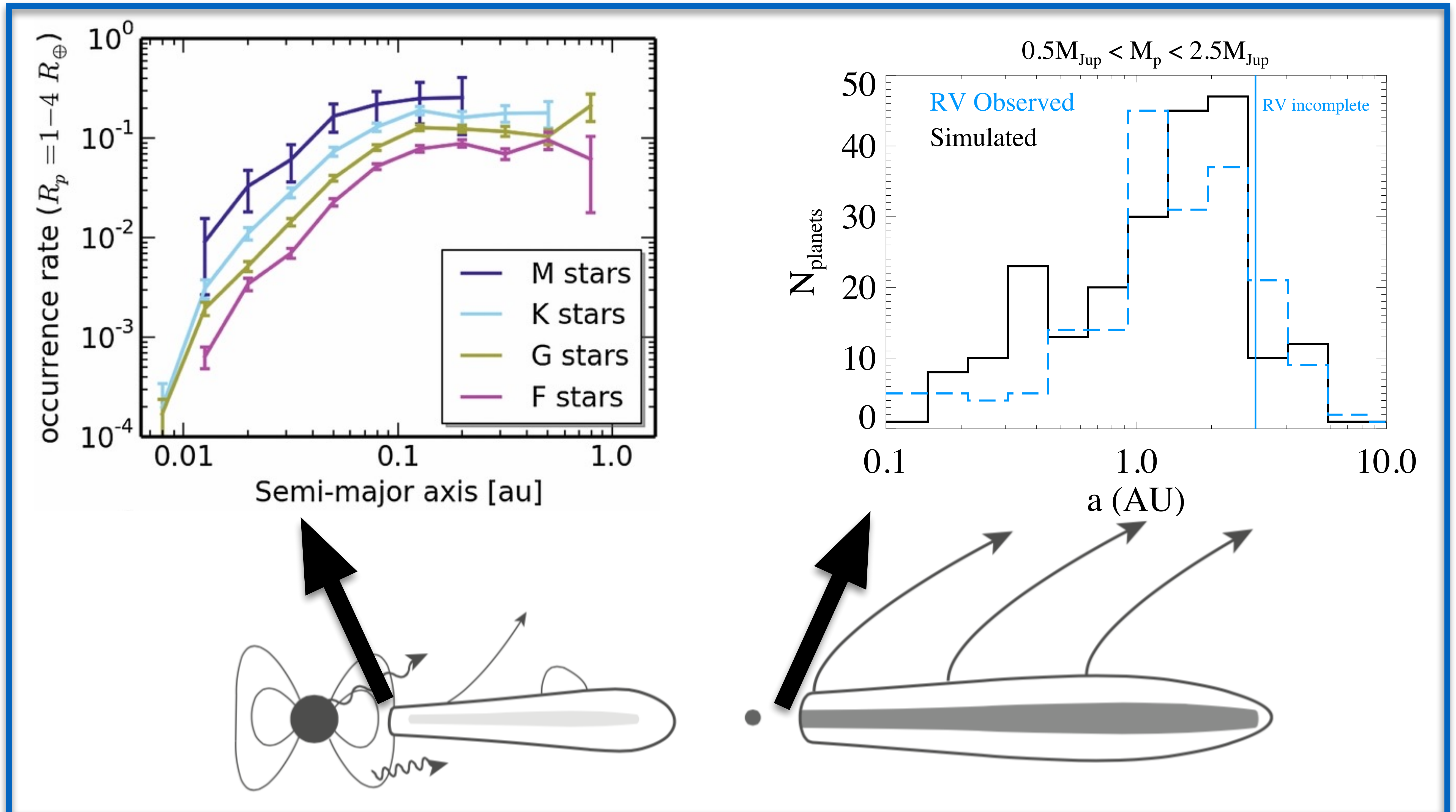


Which planet formation models reproduce best the observations?

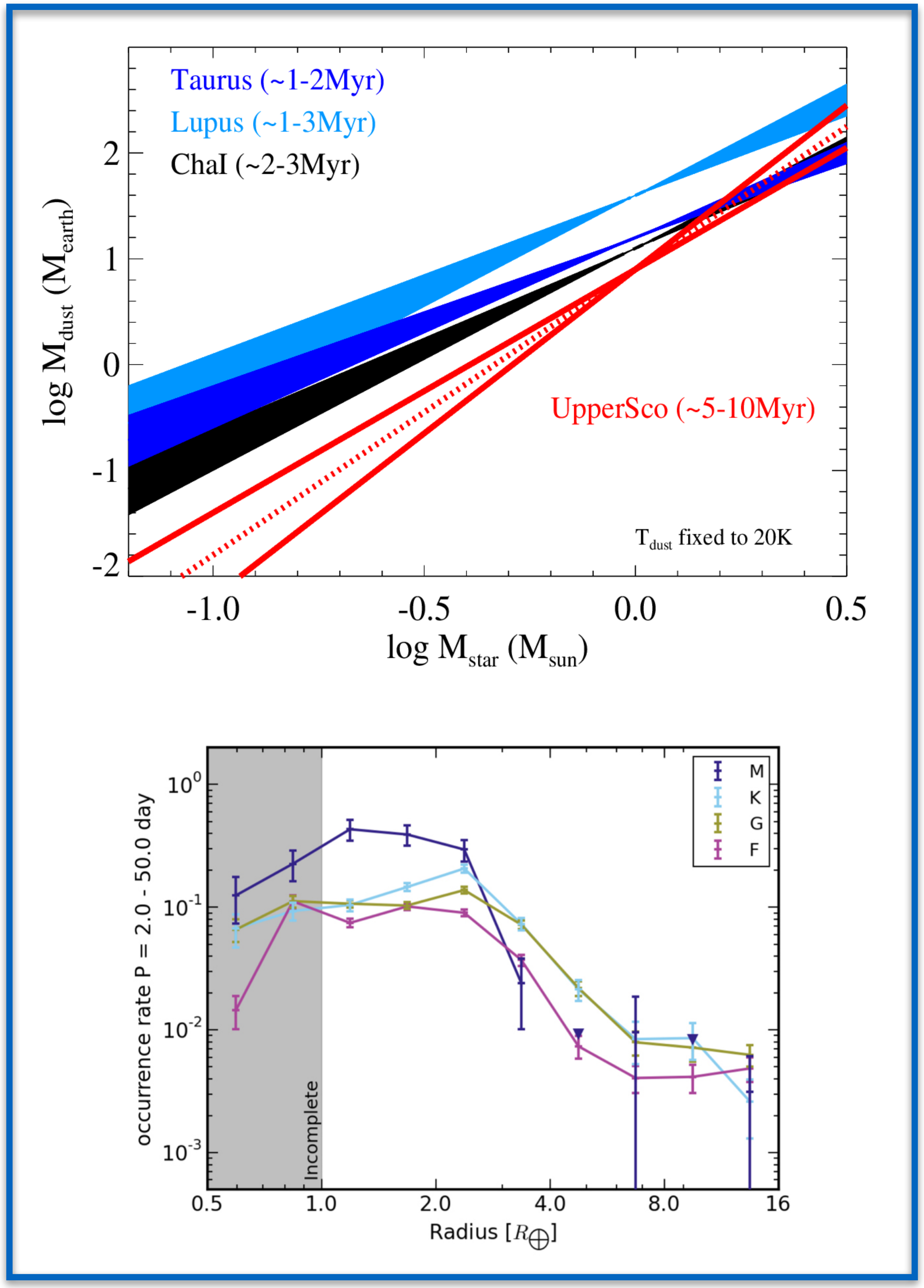
How common are systems like our Solar System?



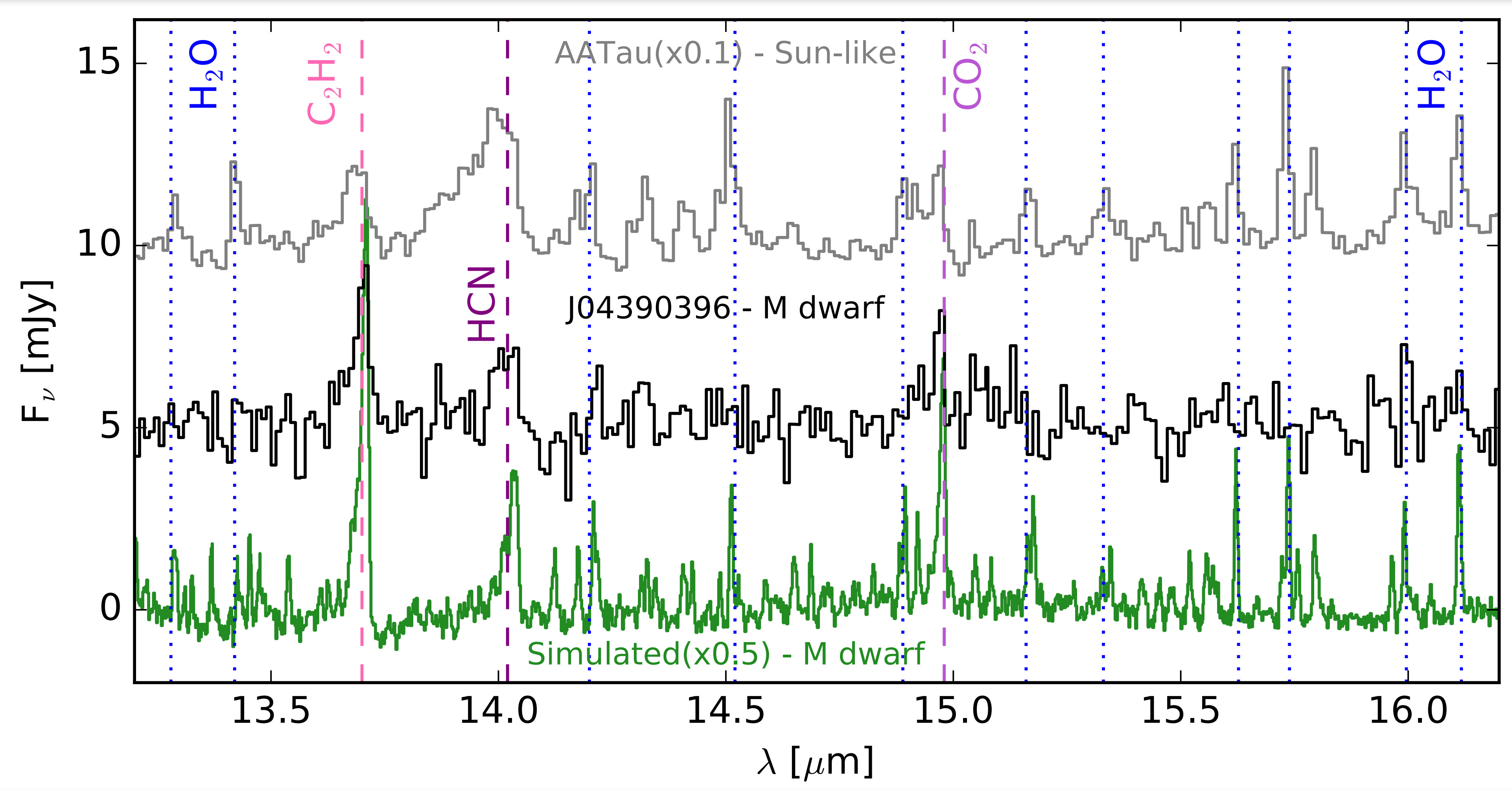
Mulders et al. in prep.



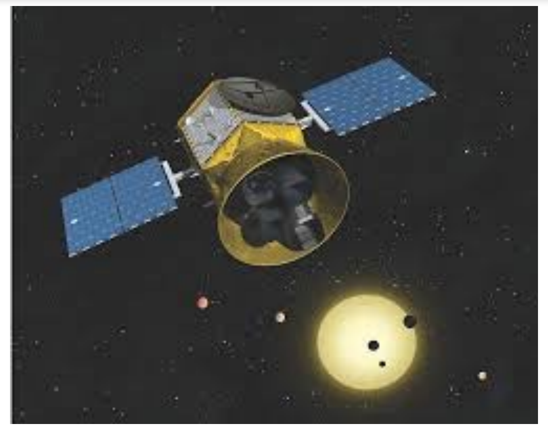
occurrence rate (R_p =1−4 $R_\oplus$)
Semi-major axis [au]
M stars
K stars
G stars
F stars
$0.5M_{Jup} < M_p < 2.5M_{Jup}$
RV Observed
Simulated
RV incomplete
$N_{planets}$
a (AU)

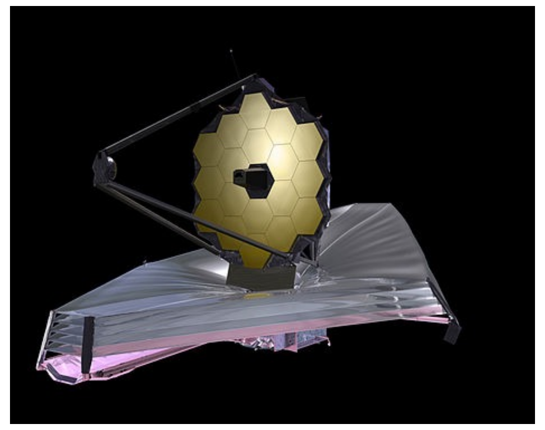


Taurus (~1-2Myr)
Lupus (~1-3Myr)
ChaI (~2-3Myr)
UpperSco (~5-10Myr)
T_{dust} fixed to 20K
log M_{dust} (M_{earth})
log M_{star} (M_{sun})
occurrence rate P = 2.0 - 50.0 day
Incomplete
Radius [$R_\oplus$]
M
K
G
F

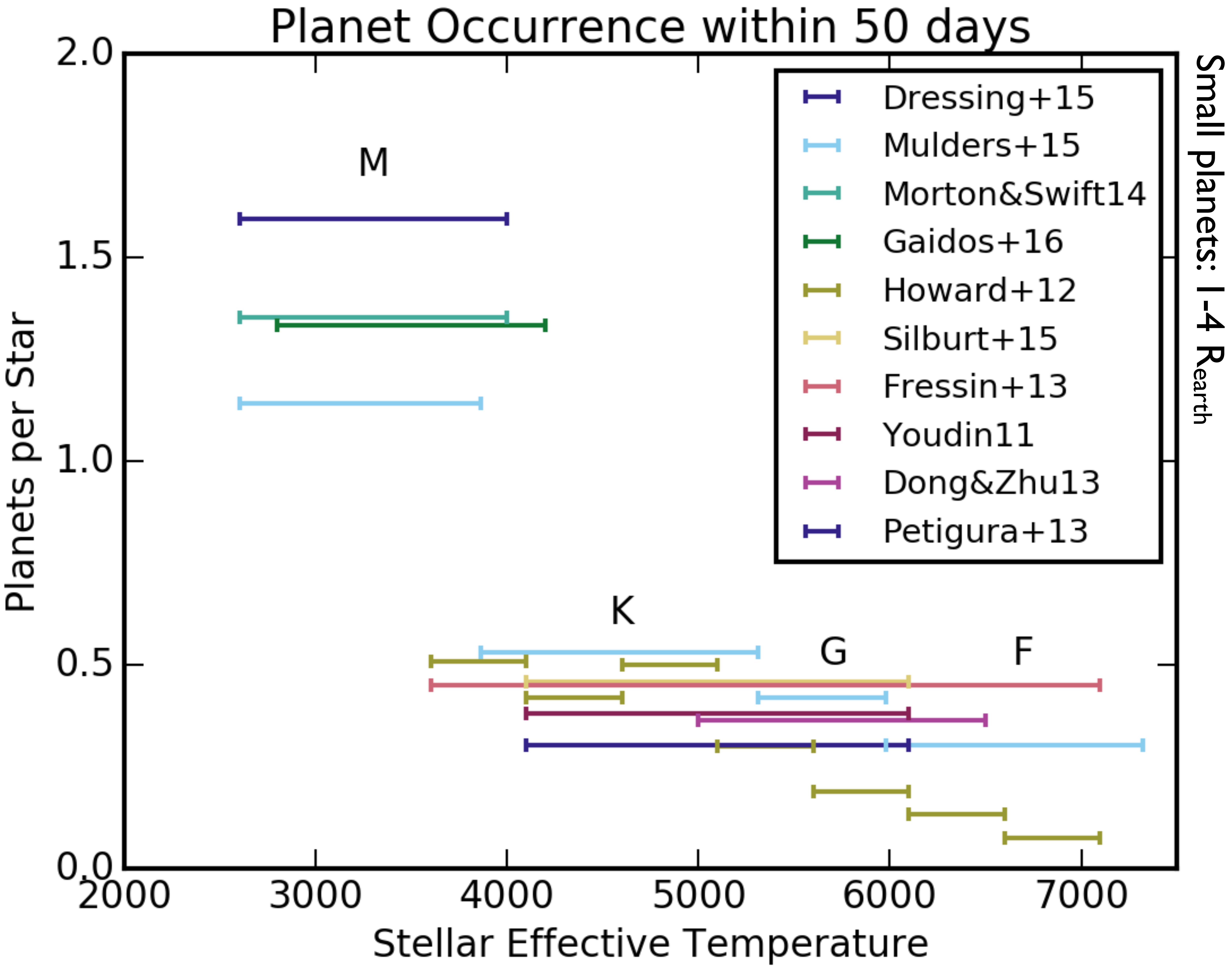


H_2O
C_2H_2
HCN
CO_2
AATau(x0.1) - Sun-like
J04390396 - M dwarf
Simulated(x0.5) - M dwarf
F_ν [mJy]
λ [μm]





Additional Slides

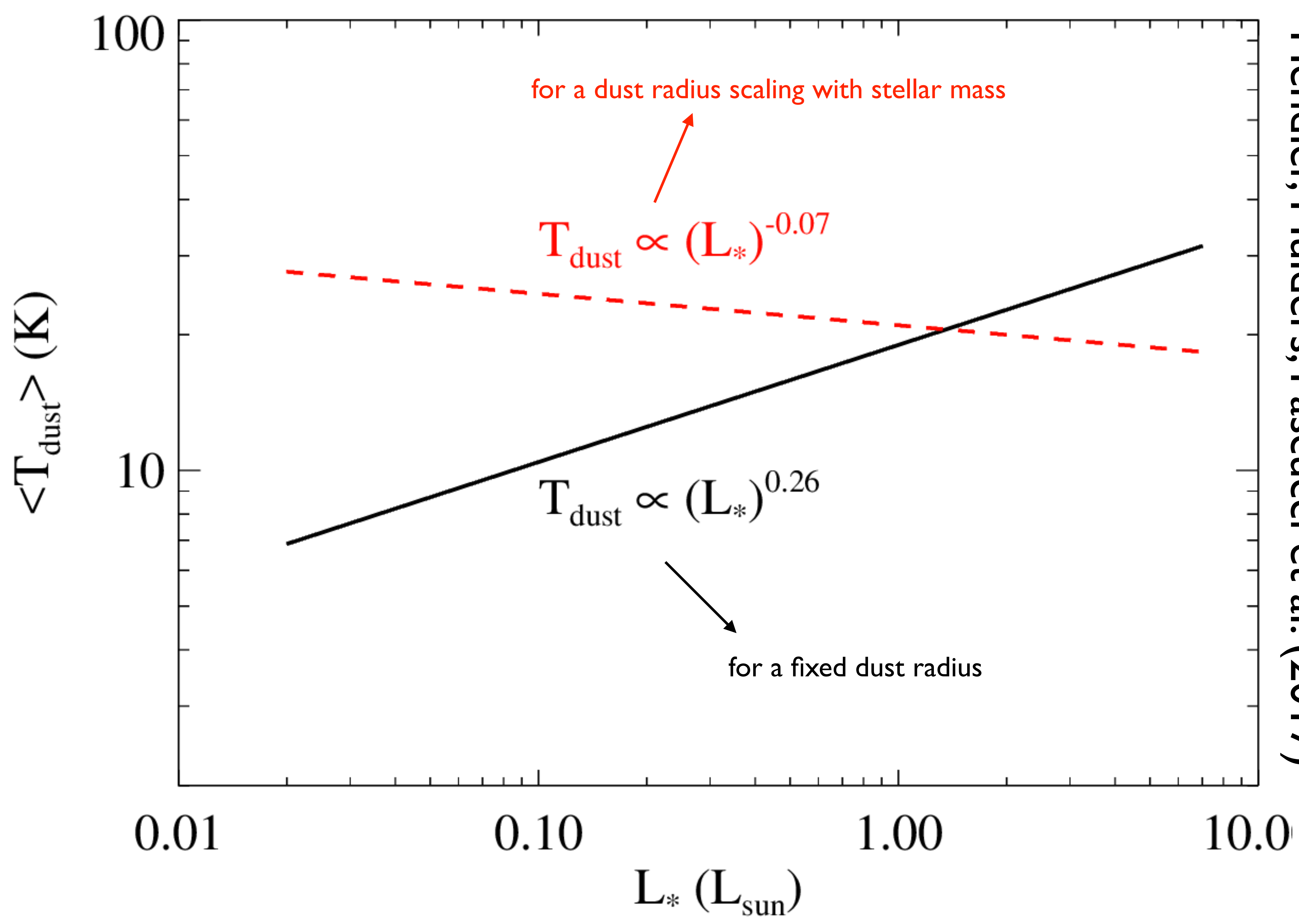


from G. Mulders (review chapter to appear in "Handbook of Exoplanets", eds. Dee & Belmonte)

Pascucci et al. (2016)

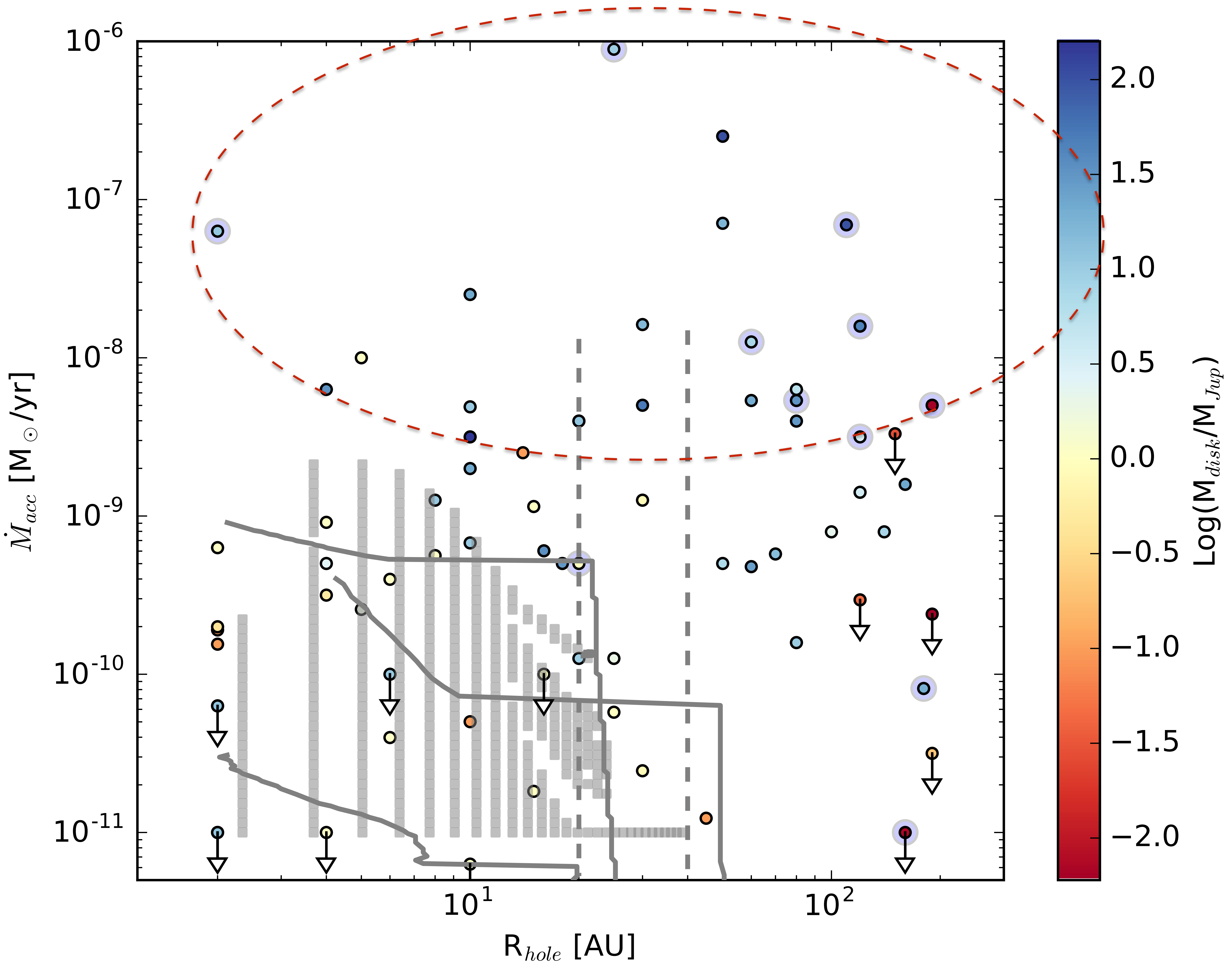
Table 4
M_{dust}–M_* Relations

Region	Age (Myr)	α_{T20}	β_{T20}	α	β	Dispersion
Taurus	1–2	1.6(0.2)	1.2(0.1)	1.1(0.2)	1.0(0.1)	0.7(0.1)
Lupus[a]	1–3	1.8(0.3)	1.6(0.2)	1.1(0.3)	1.4(0.2)	0.8(0.1)
Cha I	2–3	1.9(0.2)	1.1(0.1)	1.3(0.2)	1.1(0.1)	0.8(0.1)
Upper Sco	10	2.7(0.4)	0.9(0.2)	1.9(0.4)	0.8(0.2)	0.7(0.1)



Hendler, Mulders, Pascucci et al. (2017)

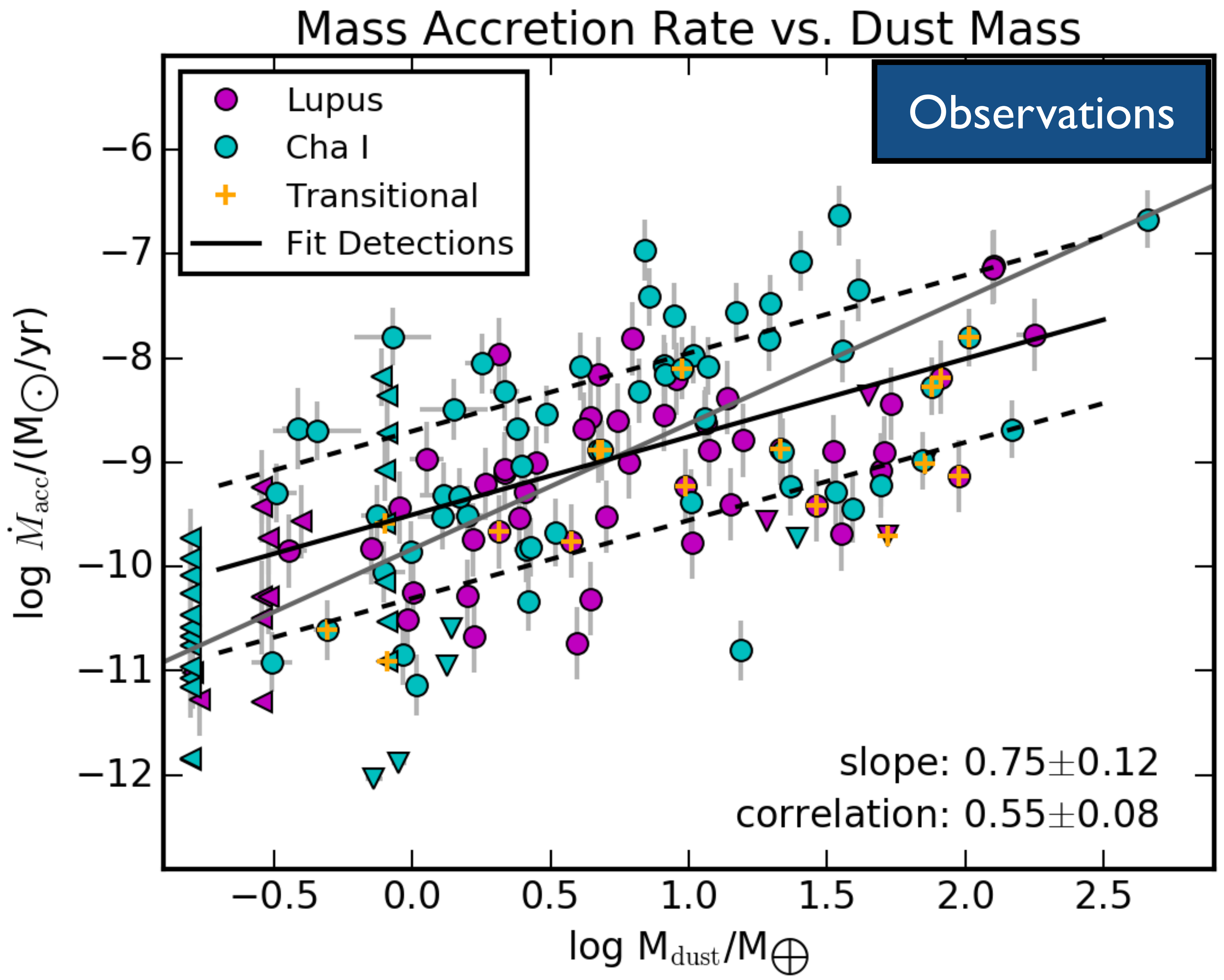
Not all transition disks are dispersing disks!

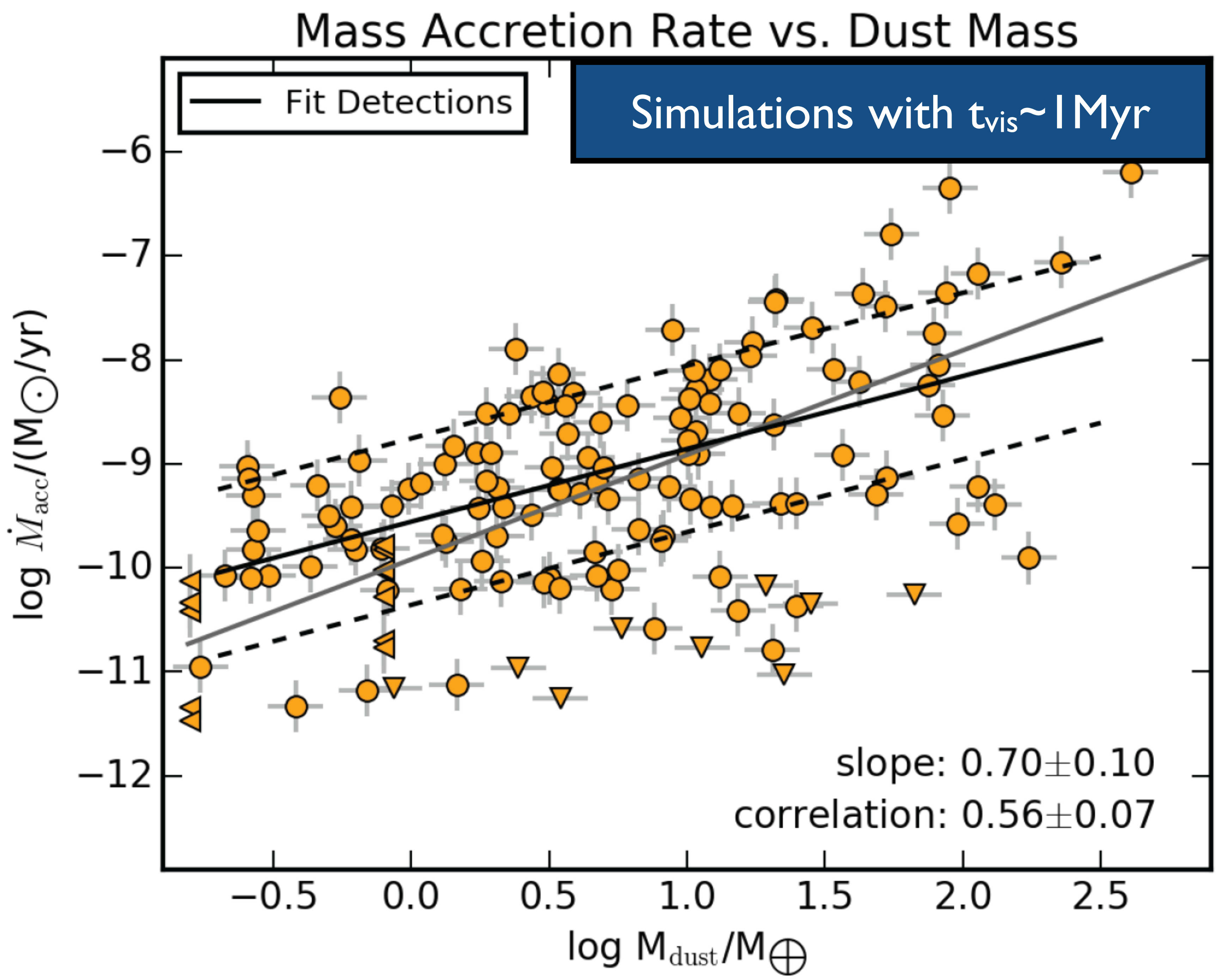


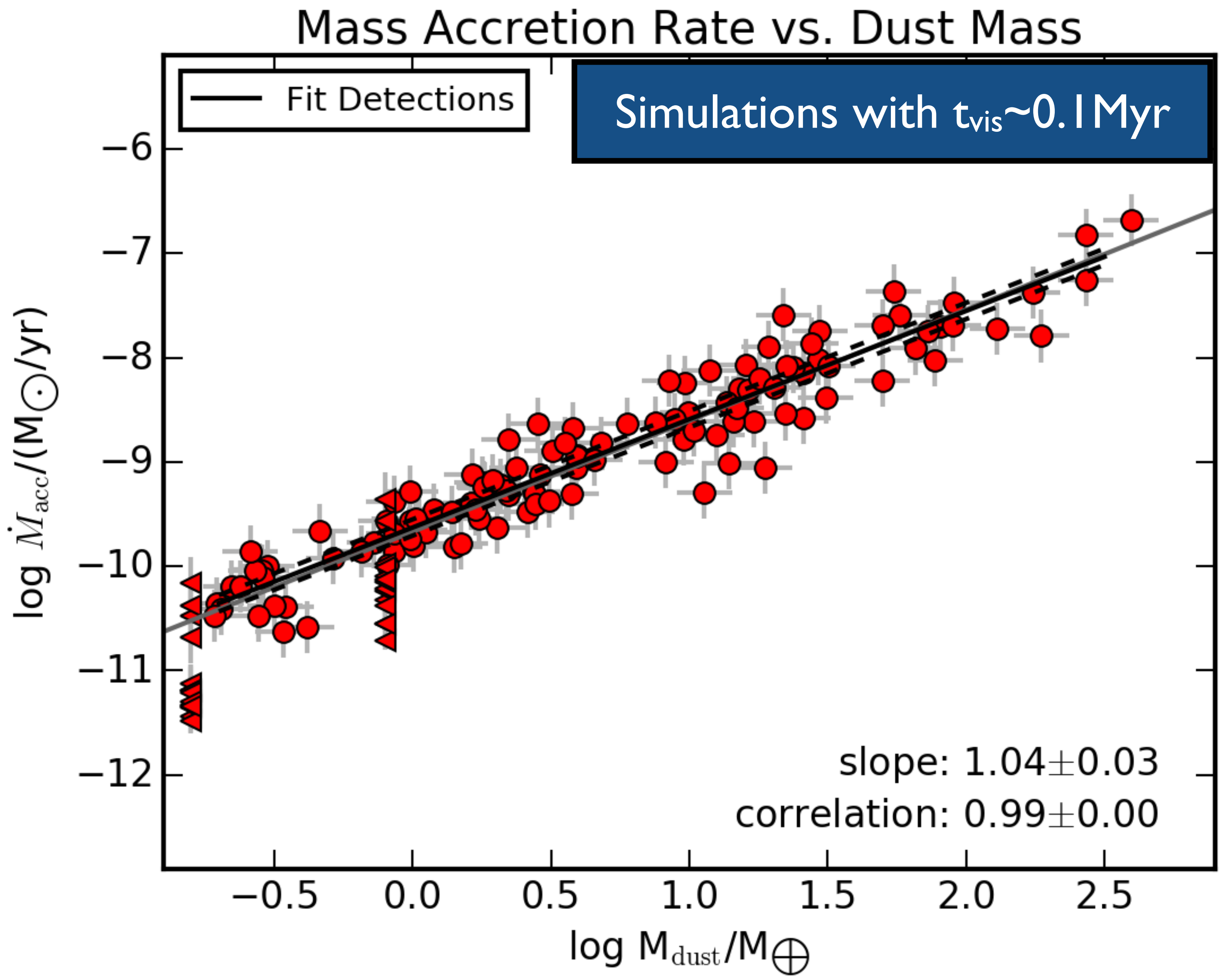
How can we explain the population of high accreting transition disks?

Twenty-nine out of 72 discs (approx. 40%) are consistent with dust cavities open by photoevaporation

From the review article of Ercolano & Pascucci (2017)





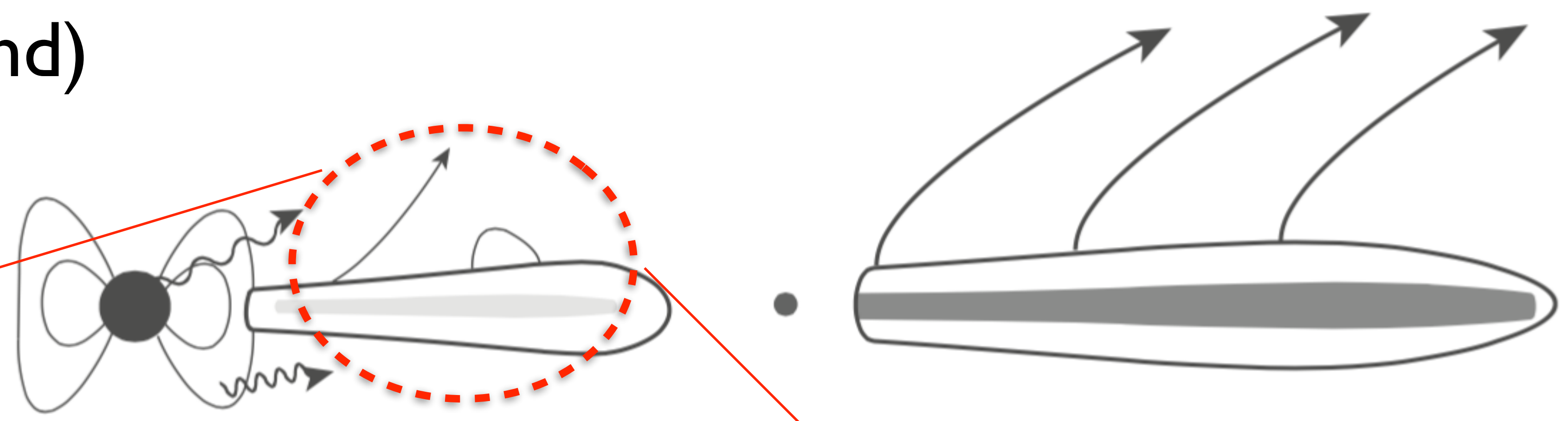


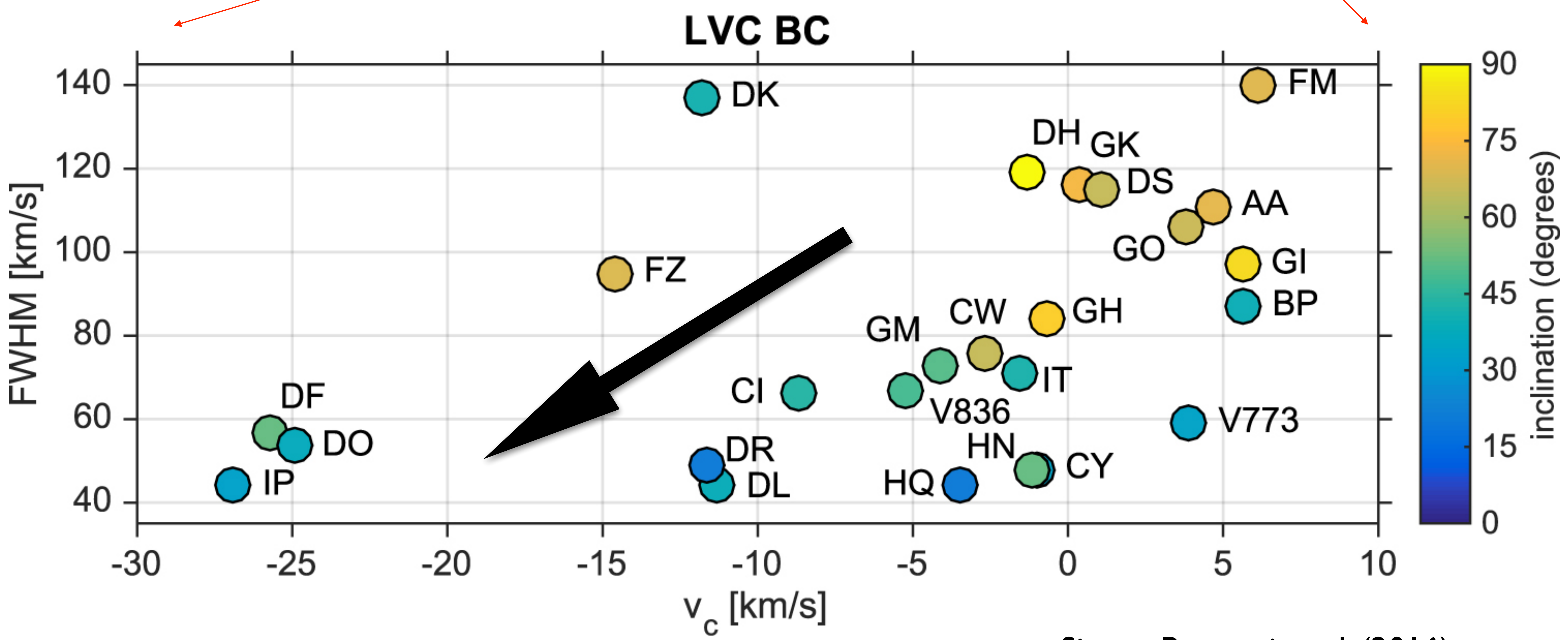
The scatter in Macc-Mdust can be reproduced IF the viscous timescale is long (a few Myr), i.e. disks have not substantially evolved in the ChaI and Lupus star-forming regions.

from Mulders et al. (2017) but see also Lodato et al. (2017)

MHD winds are common!

The broad component arises inside the disk gravitational radius,
hence the flow has to be magnetically driven (MHD wind)



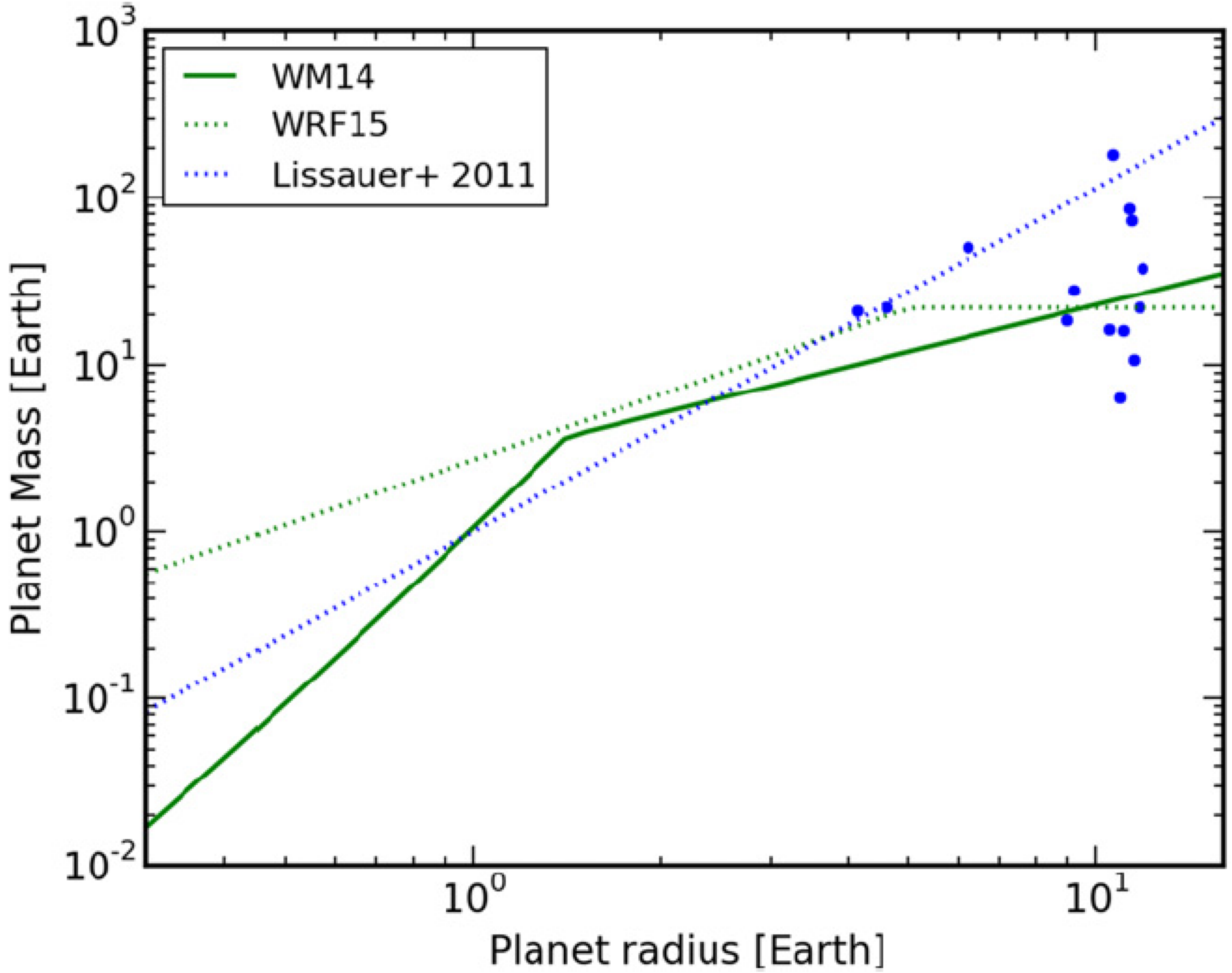


Simon, Pascucci et al. (2016)

$\boxed{\text{Scaling relation for the gap (photoevaporation): } R_{crit} \sim M_{star}/c_s^2}$

$\boxed{\text{Snowline (accretion): } R_{sn} \sim (M_{star})^{1/3} \times (M_{acc})^{4/9} \sim (M_{star})^{1.2}}$

$\boxed{\text{Snowline (irradiation): } R_{sn} \sim (L_{star})^{1/2} \sim (M_{star})^2}$



Mulders et al. (2015b)

dwarfs: 134796, Rst= 0.91, Mst=0.90
K: 27077, Rst= 0.71, Mst=0.72
M: 3229, Rst= 0.38, Mst=0.39
G: 57292, Rst= 0.90, Mst=0.87
F: 47089, Rst= 1.07, Mst=1.08

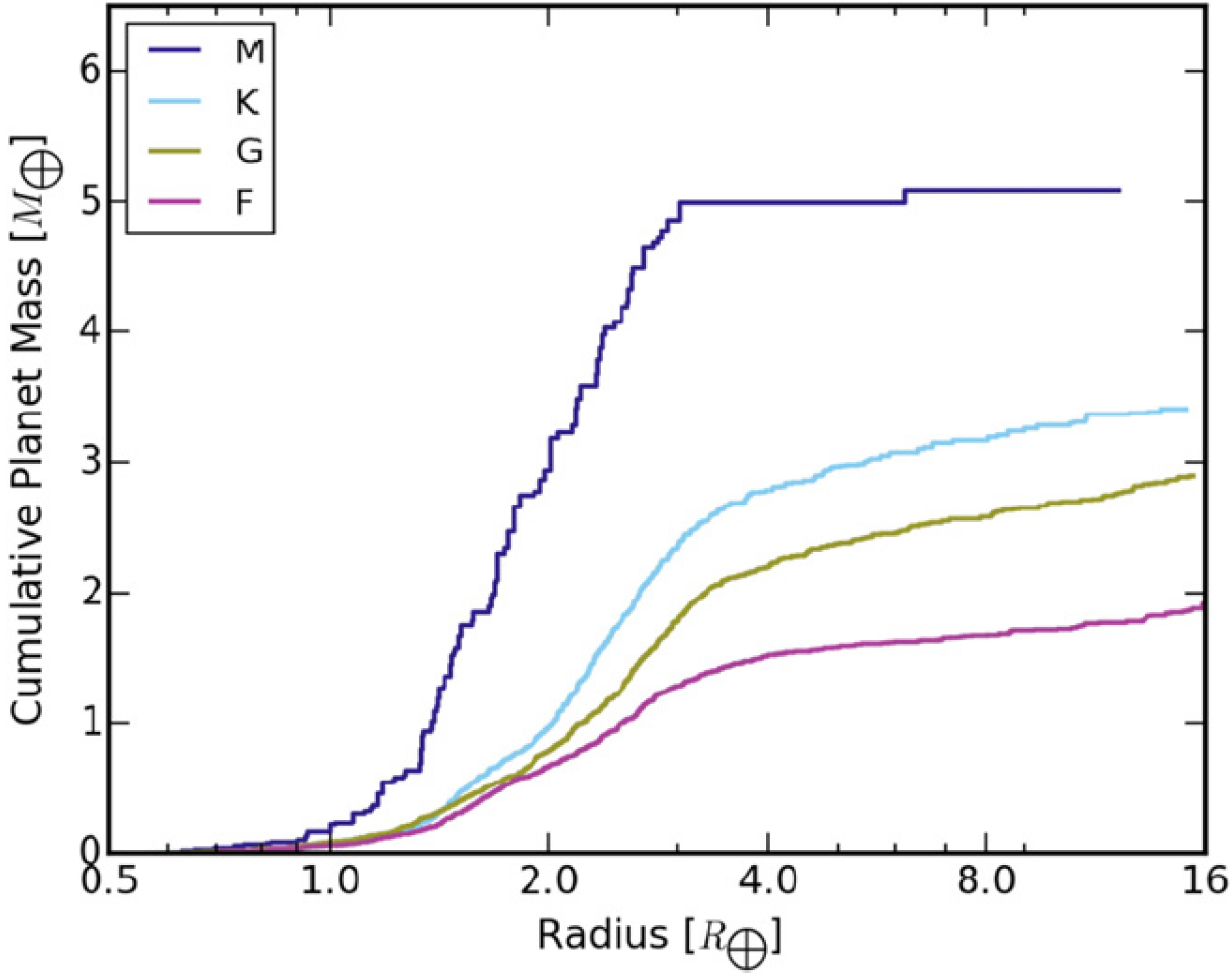


Figure 7. Planet radius distribution (left) and cumulative planet mass per star (right) for orbital periods between 2 and 50 days for M, G, K and F stars. The bins in the upper panel are twice as wide as in Figure 1.

Mulders et al. (2015b)

Power-law Index of Turnover Radius as Function of Stellar Mass for the Different Truncation Mechanisms Discussed in Section 4.1

Mechanism	Location	Assumption	Equation
Co-rotation	$M_*^{1/3}$		11
Sublimation	$M_*^{0.7}$	$L_{\rm PMS} \propto M_*^{1.4}$	12
	$M_*^{11/9}$	$q = 2$	13
	$M_*^{7/9}$	$q = 1$	13
Tides (stellar)	$M_*^{9/13}$	$R_* \propto M_*$	15
Tides (planetary)	$M_*^{3/13}$		16

Mulders et al. (2015a)